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THESIS

AN ANALYSIS OF DEGRADED COMMUNICATIONS IN THE ARMY'S FUTURE FORCE

by

Joseph M. Lindquist

June 2004

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The US Department of Defense is currently pursuing the most comprehensive transformation of its forces since the early years of WWII. This transformation is a holistic approach to update both the equipment that the forces will fight its conflicts with and the way in which they will fight. This transformation relies heavily on fully networked air, ground and space based platforms. While many experts agree that in the course of the next 10 years communications equipment will emerge to support the networking of these systems, there remains much uncertainty on how operations will be effected if the technology does not mature enough to meet expectations. This research shows that even a 25 percent degradation in communications range could pose significant challenges for this Future Force. Additionally, even small delays (latencies greater than one minute) and constraints on network throughput can increase the Future Force casualties and the duration of battle. While the end result in all analysis shows that the Future Force is a superior element with the same battle end state—victory, the cost of that victory depends significantly on effective communications.

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AN ANALYSIS OF DEGRADED COMMUNICATIONS IN THE ARMY'S FUTURE FORCE

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requirements for the degree of

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ABSTRACT

The US Department of Defense is currently pursuing the most comprehensive transformation of its forces since the early years of WWII. This transformation is a holistic approach to update both the equipment that the forces will fight its conflicts with and the way in which they will fight. This transformation relies heavily on fully networked air, ground and space based platforms. While many experts agree that in the course of the next 10 years communications equipment will emerge to support the networking of these systems, there remains much uncertainty on how operations will be effected if the technology does not mature enough to meet expectations. This research shows that even a 25 percent degradation in communications range could pose significant challenges for this Future Force. Additionally, even small delays (latencies greater than one minute) and constraints on network throughput can increase the Future Force casualties and the duration of battle. While the end result in all analysis shows that the Future Force is a superior element with the same battle end state—victory, the cost of that victory depends significantly on effective communications.

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THESIS DISCLAIMER

The reader is cautioned that the computer programs presented in this research may not have been exercised for all cases of interest. While every effort has been made, within the time available, to ensure that the programs are free of computational and logic errors, they cannot be considered validated. Any application of these programs without additional verification is at the risk of the user.

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LIST OF KEY WORDS, SYMBOLS, ACRONYMS AND ABBREVIATIONS

ABM	Agent-Based Models
AoA	Analysis of Alternatives—Evaluation of operational effectiveness and costs of alternative materiel systems in the acquisition process.
ARV-A	Armed Robotic Vehicle—Assault Variant.
ARV-RSTA	Armed Robotic Vehicle—Reconnaissance, Surveillance, and Target Acquisition Vehicle.
Bandwidth	The range of frequencies, expressed in kilobits per second, that can pass over a given data transmission channel within a network. The bandwidth determines the rate at which information can be sent through a channel—a greater bandwidth results in more information that can be sent in a given amount of time.
BLOS	Beyond Line of Sight—This describes weapon platforms that employ a combination of organic three-dimensional sensors and networked fires to establish the sensor to shooter linkage. This type of direct fire engagement extends the range of direct fire LOS capability, e.g., tank main guns.
CA	Combined Arms—Warfare in which infantry, artillery, air support, intelligence, and other key elements are all coordinated for maximum effect.
CROP	Common Relevant Operational Picture
DA	Department of the Army
DoD	Department of Defense
FCS	Future Combat Systems
GUI	Graphical User Interface

ICV	Infantry Carrier Vehicle
LOS	Line of Sight—This describes weapon platforms where the sensor, decider, and shooter are part of the same system. This type of engagement assumes some degree of exposure on the part of the shooting platform and generally undeviating ballistic trajectory, e.g., rifles and machine guns.
MCS	Mounted Combat System
MOUT	Miltiary Operations in Urbanized Terrain
NLOS	Non-Line of Sight—This describes weapon platforms where the sensor, decider, and shooter are not part of the same echelon. The sensor detects a target, the decider tasks the shooter, and the shooter shoots. This type of engagement assumes no exposure of the shooter to the target, e.g., mortars, cannons and missiles.
SoS	Sum of Squares—this is a measure of the variability in the response due to a particular factor or combination of factors in a regression fit.
TRAC	Training and Doctrine Command Analysis Center
TRADOC	Training and Doctrine Command
UA	Unit of Action—Modular brigade level maneuver force (~1200 soldiers). Commands 2-4 Combined arms battalions.
UE	Unit of Employment—Modular division level maneuver force (~15,000 soldiers). Commands 4-5 Units of Action.
WSMR	White Sands Missile Range

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I would like to begin by thanking the Lord for creating me and giving me the challenges that this life offers. It is only through these challenges that I have been able to grow as a person and a believer in body of Christ.

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EXECUTIVE SUMMARY

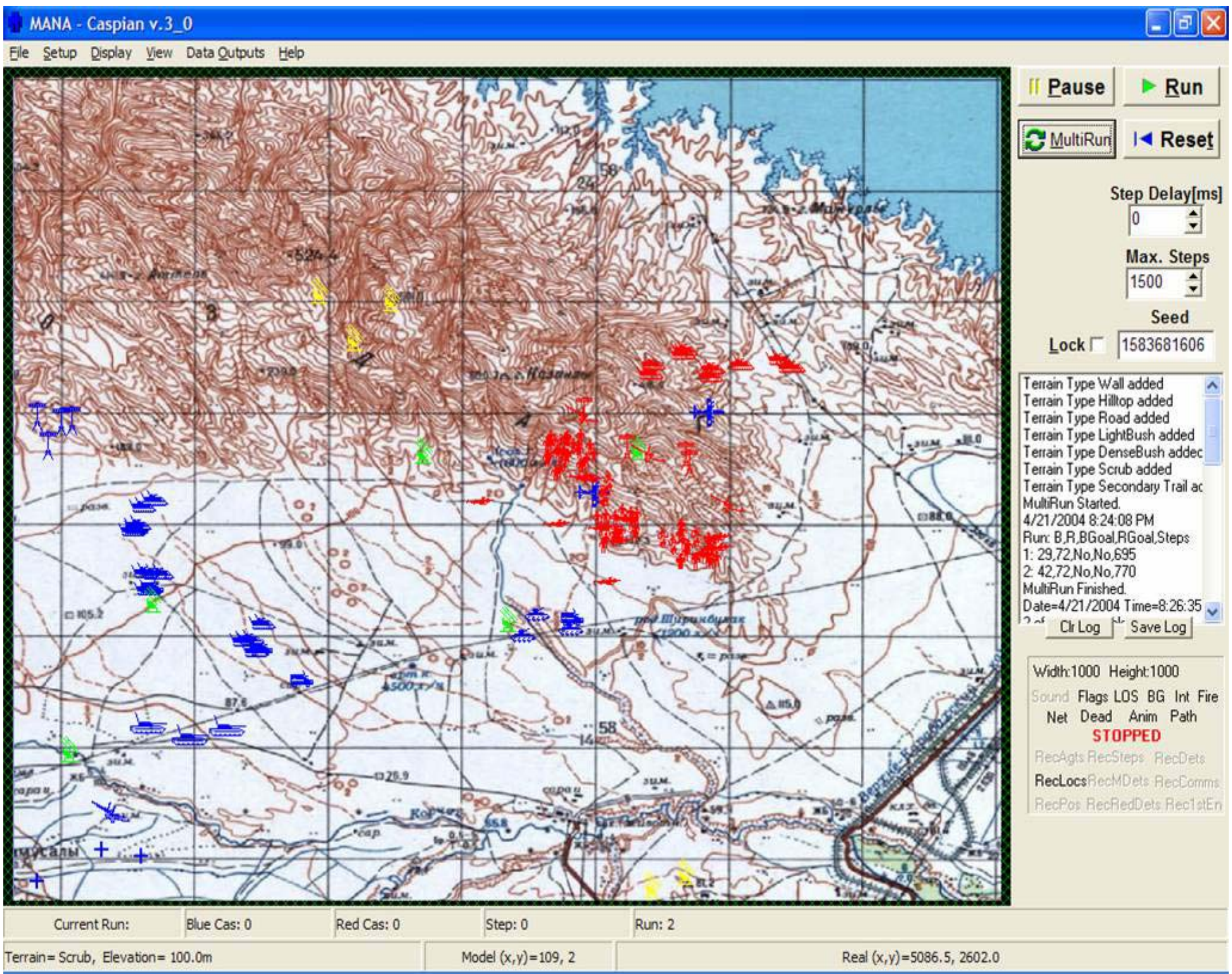
The United States Department of Defense (DoD) is currently pursuing the most comprehensive transformation of its forces since the early years of World War II. This transformation is a holistic approach to update both the equipment that the forces will fight its conflicts with and the way that they will fight the conflicts. Incorporating emerging technology with revolutionary tactics, the primary goal of the US Army transformation is the development of the Future or Objective Force.

The Future Force is characterized by a lighter, more agile force that is able to deploy faster, seize the initiative and finish decisively. Since legacy systems are inadequate to facilitate all of the goals of DoD transformation, the Department of the Army is developing the core building block of the Future Force known as the Future Combat System (FCS) Family of Systems (FoS). The FCS takes advantage of advances in battlefield sensing, fire control and lethality to allow the battlefield commander to engage the enemy at standoff, diminishing their will to fight while mitigating friendly losses.

Engaging an enemy at standoff using unmanned sensors assumes a line of communications that will enable the transfer of the information that the "hunters" observe to the "killers" for action. While many experts agree that over the course of the next 10 years communications equipment will emerge to support the networking of these systems, there remains much uncertainty on how operations will be affected if the technology does not mature enough to meet expectations or enemy electronic attack assets are employed to disrupt friendly operations. This research focuses on the FCS employed in the attack against a prepared and well fortified defensive enemy when communication degradation is experienced in one or many battlefield operating systems.

To uncover insights on the effects of degraded communications, a scenario was created in Map Aware Non-Uniform Automata (MANA), an agent-based simulation designed for examining many possible factors over many settings using a technique known as data farming. Using the state-of-the-art experimental designs outlined in this thesis, over 50,000 individual simulations provided the data to uncover insights on what happens if communications do not work "as advertised."

This scenario replicates a battle vignette previously analyzed by Training and Doctrine Command Analysis Center, White Sands Missile Range, on a physics-based simulation called JANUS. This physics-based simulation, however, did not take the effects of degraded communications into account. The area of operations was digitized into MANA and individual fighting systems were created to closely represent the FCS designs. A screen shot of the final battlefield configuration is shown below.

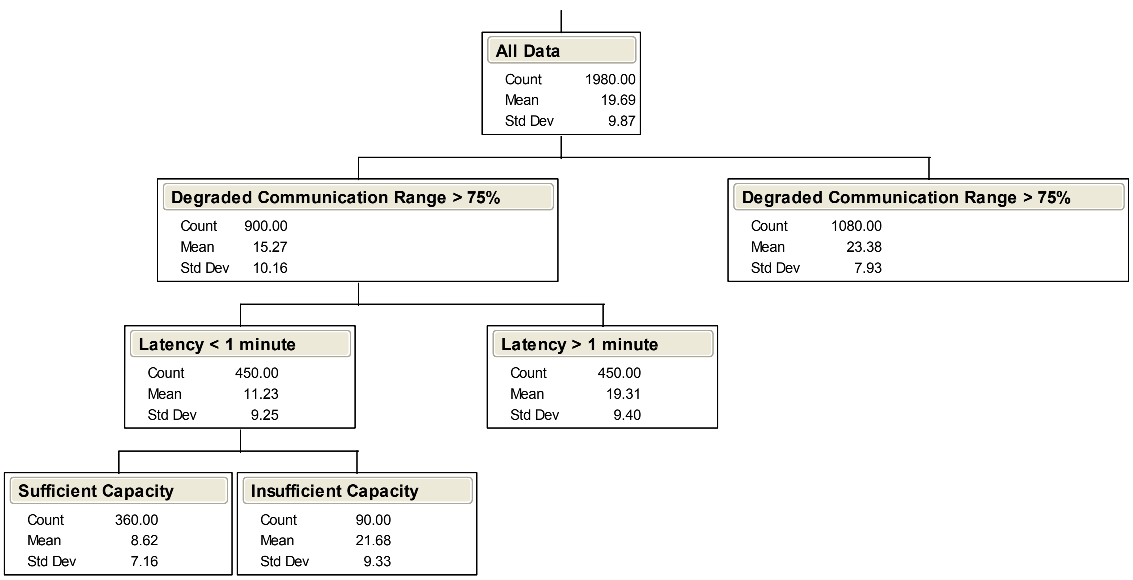


The results of this thesis work suggest the following:

- While it is believed that communication range will not be an issue with evolving communications equipment, the Army must be sure of this. Even a degradation of 25 percent on the ability to communicate over the entire battlespace could have dramatic consequences for the FCS.

- An unresponsive or slow network is nearly as detrimental to the FCS as diminished communications range. It has been shown in this analysis that when intelligence on a fairly static enemy employed in the defense is delayed, the length of battle is extended and Blue forces generally pay for that delay in casualties.

The significance of these communications factors are shown in the regression tree below. This tree shows that when communications allow the FCS to relay intelligence over at least 75 percent of the battlespace, network latency is less than one minute, and throughput of the network is "sufficient," the expected number of Blue casualties is around nine. In comparison, when communication range is degraded more than 25 percent, the result is nearly three times the expected number of FCS casualties.



Additional findings include:

- Reliability, while important, is not as significant in a system with many means of redundancy (such as the FCS). Even if a substantial amount of communication links are unable to relay enemy intelligence, there are many others that are able to "pick up the slack."

- Enemy electronic warfare assets must not be underestimated and should be a focus of any pre-engagement intelligence activities. As indicated in this research, even a limited attack focused on a particular battlefield operating system (armor assets), could prove to be costly for the FCS.
- The increased lethality of the non-line of sight systems, when performing as specified, present an incredible asset which can set the tone for FCS battlefield success and must be allowed to attrite the enemy as long as possible.
- It is worth noting that even with the technologically advanced future force, traditional determinants of battle outcome (leadership, enemy posture, friendly and enemy morale) will still be just as important to victory. As General George Patton once said, “It is the unconquerable nature of man and not the nature of the weapon he uses that ensures victory."

The largest take-away from this analysis is that a viable communication network *IS* important to the FCS. This network requires special attention when designing its characteristics and should be treated as a *MAIN* component of the FCS. If a communication network is unable to support the integration of all of the battlefield operating systems, the increased mobility, sensing and targeting abilities of the FCS are diminished.

I. INTRODUCTION

> *The need for military transformation was clear before the conflict in Afghanistan and before September 11th.... What's different today is our sense of urgency—the need to build this future force while fighting a present war. It's like overhauling an engine while you're going 80 miles an hour. Yet we have no other choice.*
>
> President George W. Bush
>
> At the Citadel, Charleston, SC December 11, 2001

A. TRANSFORMATION BACKGROUND

The United States Department of Defense (DoD) is currently pursuing the most comprehensive transformation of its forces since the early years of World War II. This transformation is a holistic approach to update both the equipment that the forces will fight its conflicts with and the way that they will fight the conflicts. Incorporating emerging technology with revolutionary tactics, the primary goal of the US Army transformation is the development of the Future or Objective Force.

A look at recent US conflicts reveals a strategy of "fight after force buildup." When viewed from the context of Operations Desert Shield, Desert Storm, Enduring Freedom, and Iraqi Freedom this philosophy was very successful. These conflicts allowed for a time period where forces were massed in theater, followed by buildup of logistic effort, and ending in advance against the enemy. Future conflict, however, may not allow for this massive buildup before employment. In addition, the face of the future enemy is changing from regional state powers to a more asymmetric threat that may require an entirely different strategy and equipment mix.

Retired General Norman Schwarzkopf, when characterizing the future of armed conflict following Desert Storm, said: "I am quite confident that in the foreseeable future armed conflict will not take the form of huge land armies facing each other across extended battle lines on the field of battle. Conflict in the future will be similar to that which we have seen in the recent past. Both of the military operations in which we were involved with in the Middle East were the result of regional conflicts that grew to proportions that began to impact the rest of the world. Such dangerous regional conflicts will be with us for years to come. Any one of them could lead us to war."[1]

The future operational environment poses complex, adaptive and asymmetric threats equipped with advanced technologies. Thus, the key to Army Transformation is on developing equipment that will be flexible and mobile enough to employ land forces that are decisive at every point on the spectrum of military operations. The mid 1990's standard of deploying 5+ divisions within 75 days, according to many within the Department of the Army (DA), is a luxury that the force will not have in future conflict.

With all of this said, leadership in the DoD and DA are pushing forward with the Army's Future Force. The Future Force is characterized by a lighter, more agile force that is able to deploy faster, seize the initiative and finish decisively. Since legacy systems are inadequate to facilitate all of the goals of DoD transformation, the DA is developing the core building block of the Future Force known as the Future Combat System (FCS) Family of Systems (FoS). Optimized for strategic versatility, this equipment is designed to be C-130 and C-17 transportable for quick response to any theater.[2] Army transformation requirements for this force include the ability to put a combat-capable brigade anywhere in the world within 96 hours, a full division in 120 hours, and five divisions on the ground within 30 days.[3] The idea driving the design of the FCS is that with a change in the way the Army fights, it can trade "a pound of armor for a pound of information."[4]

There are two critical enabling capabilities required to make the vision of the Future Force tenable. The first is the requirement of high situational understanding and the second is decisive tactical combat. Situational understanding allows the commander to enter the conflict on his terms and seize the initiative through knowledge of both his

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1 H. Norman Schwarzkopf, *General H. Norman Schwarzkopf: the autobiography: it doesn't take a hero / written with Peter Petre*, (New York: Bantam Books, 1992), p. 502.

2 US Army Training and Doctrine Command, *The Army Future Force: Decisive 21st Century Landpower Strategically Responsive, Full Spectrum Dominant*, (Fort Monroe, VA, August 2003), Retrieved 5 May 2004 from the World Wide Web at http://www.tradoc.army.mil/dcsdcs , pp. 1-5.

3 Global Security.org, *Future Combat Systems*, Retrieved 31 March 2004 from the World Wide Web at http://www.globalsecurity.org/military/systems/ground/fcs.htm .

4 Colonel Jeff Appleget, *Future Combat System (FCS) Analysis of Alternatives (AOA) Briefing, (Given to NPS Operation Analysis students),* 14 August 2003.

and the enemy's forces. Decisive tactical combat refers to the advanced capabilities with respect to mobility and long-range precision fires, which enables the commander to engage and attrite the enemy at standoff.[5]

With the previous conceptual information on the FCS, the reader may be curious as to the physical description of the FCS. The FCS consists of mobile platforms (most are armored) that are organized according to primary functions. Such functions include Line-of-Sight (LOS) / Beyond-Line-of-Sight (BLOS) / Non-Line-of-Sight (NLOS) weapon systems, Command and Control, Communications, Computers, Intelligence, Surveillance and Reconnaissance (C4ISR) platforms, soldier platforms, and support platforms. Each platform is designed to operate in concert with the others to provide the tactical commander with a common relevant operational picture (CROP) of the battlefield. To simplify, the FCS employs platforms in different roles. One role is as the hunter—these describe systems designed to detect, classify and provide targeting information to other platforms. The second role is as the killer—these describe systems that are designed to use organic and inorganic situational awareness to deliver killing power on the enemy.

In addition to developing new equipment for the force to fight its conflicts with, transformation also includes a second main component: developing new tactics that the force will fight with. In order to meet this component, the Army has developed an Operational and Organizational plan to reorganize the current fighting force and develop tactics that are consistent with employing the technology. The driving idea of this plan is that to enable flexible and mobile land forces, the main fighting unit must be a modular and tailorable force.

Under the Future Force nomenclature, the Unit of Action (UA) is the term used for the Brigade (~1200 soldiers). Units of Acton (UA) are the tactical warfighting echelons of the Objective Force and command 3-4 combined arms (CA) battalions. The Unit of Employment level 1 (UE1) is the term used for today's Divisions (~15,000 soldiers). Each UE1 is designed to command 4-5 UAs but also maintain and support the warfighting elements. Units of Employment are the basis of combined arms air-ground

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5 US Army Training and Doctrine Command, *The Army Future Force: Decisive 21st Century Landpower Strategically Responsive, Full Spectrum Dominant*. p. 4-5.

task forces that resource and execute combat operations; designate objectives; coordinate with multi-service, interagency, multinational and non-governmental activities; and employ long range fires, aviation and sustainment. They also provide C4ISR and tactical direction to UAs.

The tactics, while varied for any given mission, make use of the developing technologies that allow the unit to effectively engage and attrite the enemy at greater ranges without commiting significant numbers of ground forces until operationally advantageous. A sample attack operation might include a period of reconnaissance by unmanned air and ground systems, followed by engagement by NLOS fires, BLOS and finally LOS fires and ground force commitment. The NLOS and BLOS fires are directed by the unmanned air and ground systems, and LOS fires are employed once the momentum and battlespace shaping favors the attacking element.

Engaging an enemy at standoff using unmanned sensors assumes a line of communications that will enable the transfer of the information that the "hunters" observe to the "killers" for action. While many experts agree that over the course of the next 10 years communications equipment will emerge to support the networking of these systems, there remains much uncertainty on how operations will be affected if the technology does not mature enough to meet expectations or enemy electronic attack assets are developed to disrupt friendly operations.

The secret of war lies in the communications.

Napoleon Bonaparte

B. COMMUNICATIONS: THE FCS ENABLER

As discussed thus far, the Army's FCS relies heavily on timely and accurate text, voice and video communications to provide the CROP to the tactical commander. As defined by the Operational Requirements Document for the FCS, "the network must be dependable and capable of functioning degraded, [greater than 80 percent (threshold) and 98 percent (objective) static, and greater than 75 percent (threshold) and 90 percent (objective) mobile]."[6] In addition to inherent technical issues with radio and satellite based communications, as an old military proverb describes, "the enemy gets a vote too." While the FCS network must be able to operate reliably with all of its moving pieces and parts which make it function, it must also be able to do this in the presence of an enemy trying just as hard to ensure that the network fails. This is known as electronic warfare (EW).

Nearly every military officer will concede that at some point in their career, poor tactical communications hampered their ability to fight. United States Secretary of Defense Donald Rumsfeld, commenting about lessons that apply to future combat said, "…the ability of forces to communicate and operate seamlessly on the battlefield will be critical to our success."[7] The US Army Chief of Signal, MG John Cavanaugh summarizes the importance of tactical communication to warfighting by saying: "The next war will be won or lost based on the [Signal] Regiment's ability to get information to the warfighter; the victor will be the one with 'information dominance.'"[8]

In a recent General Accounting Office (GAO) report, the FCS program drew much criticism about the maturity of the technology designed to make up for the lack of armor with precision and speed. The report emphasized the design of every soldier, every drone and every armored vehicle joining together in a wireless network for combat and the difficulties with making this happen. The report asserts that this could prove to be the toughest FCS task of all, likening it to the difficulty of setting up a cell-phone system—under fire, without any towers. In addition, the information-centric nature of FCS operations requires a great deal of bandwidth to allow large amounts of information to be transmitted across the wireless network. However, the radio frequency spectrum is a finite resource with a great deal of competition and demand for it (commercial and

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6 *Operational Requirements Document for the Future Combat Systems (Change 3)*, (Unit of Action Maneuver Battle Laboratory, 14 April 2003), p. 41.

7 *Transcript of remarks delivered by Secretary of Defense Donald Rumsfeld, National Defense University, Fort McNair, Washington, D.C. Thursday, January 31, 2002*, Retrieved 4 March 2004 from the World Wide Web at http://www.defenselink.mil/speeches/2002/s20020131-secdef.html .

8 *Marketing Brochure from the Office of the Chief of Signal*, Retrieved 17 February 2004 from the World Wide Web at http://www.gordon.army.mil/ocos/rdiv/docs/Marketing percent20Brochure.pdf .

military). An internal study revealed that even if this system could be setup, FCS bandwidth demand was 10 times greater than what was actually available. [9]

Numerous examples exist of communication affecting the ability of a unit to fight. During Operation Desert Storm, one forward deployed US Marine reconnaissance unit observed the initiation of the only major Iraqi offensive mounted during the war. While observing this initiation, they found themselves unable to communicate the impending threat to the main fighting element. This situation is described by David Morris, a former Marine Officer involved in the battle, as follows:

> *8:00 PM, January 29, 1991*
> *Observation Post 4, on the Kuwaiti Border*
> *50 Miles West of Khafji, Kuwait*
>
> *Things weren't looking good for Roche. He was the comm chief and had two other radio operators under him. He was supposed to be the platoon's radio guru, and yet he couldn't raise a soul. What had he missed? He sprinted away from the berm to go check on the long-range antenna farm he'd set up in order to reach back to the rear, some 50 miles distant. Intel had told them the Iraqis didn't have any jamming capability. What else could it be? Then, thinking back, he remembered that right as their watch began, the pitch of the radio static, the ubiquitous background ssssshhhhh, had wavered ever so slightly. It seemed kinda weird at the time. Then he knew: They were being jammed.* [10]

While the results of the battle and war were in favor of the US forces, many Marines lost their lives in the course. This leads to the question: "What if the communications would have been able to overcome the enemy EW?"

A more recent and equally tragic example occurred with another Marine unit during Operation Iraqi Freedom. The battle for the bridges in Nasiriyah began early on March 23, 2003, the fourth day of the war. The mission for Charlie Company, part of the 1st Battalion, 2nd Marine Regiment out of Camp Lejeune, N.C., was to secure a bridge across the Saddam Canal on the northern edge of the city. Controlling the span was essential to opening a route for a massive Marine Expeditionary Force to attack Baghdad.

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[9] Paul L. Francis, *Defense Acquisitions: The Army's Future Combat Systems' Features, Risks, and Alternatives,* (United States General Accounting Office Washington, D.C., April 1, 2004), Retrieved 22 April 2004 from the World Wide Web at http://www.gao.gov/new.items/d04635t.pdf .

[10] David J. Morris, *Storm on the Horizon: Khafji – The Battle that Changed the Course of the Gulf War*, (New York Free Press, 2004), p. 1-2.

When the Marine units around the city lost communication, commanders became confused about the location of American troops. Subsequently, two A-10 tank killing jets were given permission by an air controller to attack what turned out to be a forward Marine company. The 15 minutes of air attacks on the friendly forces using 30-millimeter Gatling guns, Maverick missiles and bombs, ended in the destruction of two amphibious assault vehicles that were trying to evacuate wounded Marines and multiple Marine deaths due to fratricide.[11]

C. PROBLEM STATEMENT

Recognizing that the communications network is a high risk component of the FCS, the Deputy Chief of Staff of the Army for Operations (DCS G-3) tasked the US Army Training and Doctrine Command (TRADOC) with (among other items) conducting an operational analysis of the communications and computer systems network for the FCS FoS.[12] The purpose of this analysis is to evaluate the effects of network loading, network attacks, and individual system reliability on the contribution of FCS to the UA's effectiveness.

In order to evaluate these effects of the network, TRADOC first must develop a way to model the communications network. Significant effort has been exhausted in order to develop a model that will accurately model the physical effects of radio waves such as propagation, and network effects. Propagation effects are those that cause the strength of a signal to be degraded. Factors that might influence propagation include the transmission media (dense foliage, buildings of varied construction, etc.), climatic considerations (maritime, polar tundra, tropical arid and wet, etc.), and elevation of the communication nodes. Factors that might influence the network effects are queue buffer sizes, latency caused by the network, and routing protocols.

Once these models are completed, they must be incorporated into existing combat models to evaluate the effects of the communication environment on the UA's effectiveness. While there is little disagreement as to the value of accurately modeling

[11] Hector Becerra, Robert J. Lopez and Rich Connnell, *Report Details 'Friendly Fire' Casualties in Deadly Battle*, (Los Angeles Times, March 28, 2004) .

[12] Office of the Deputy Chief of Staff, G-3, *Memorandum for Commander US Army Training and Docterine Command (Director Futures Center) – Post Milestone B Analysis for Future Combat Systems (FCS),* 29 October 2003.

the physical effects of communication in order to determine the effects of degraded communication, this work is difficult, complex and still has yet to be incorporated into a combat simulation to provide insights.

This thesis will examine TRADOC's tasked analysis question concerning the effectiveness of the FCS under various network communication conditions with a lower resolution model. The overwhelming goal will be to identify the regions where communication reliability, network loading and attacks hamper the UA's ability to fight. The results of this analysis are not designed to take the place of the high resolution, physics-based modeling that is ongoing, but is focused on a lower resolution data point that can be delivered quickly on a limited personnel budget (one soldier and his thesis advisors) and a limited time budget.

D. SCOPE

There are an endless number of questions regarding how communication conditions might be affected in various operating environments. Many combinations of terrain (desert, rolling vegetation, mountains), force structures (Company, Battalion, Brigade), enemy disposition (equipment on hand, familiarity with terrain, end strength), and mission sets (attack, defense, movement to contact), exist. This thesis will focus on one such operating environment.

This analysis is focused on a UA Combined Arms Battalion in the attack using the Caspian Sea area of operations. The scenario and force structure for the analysis is taken from a Training and Doctrine Analysis Center—White Sands Missile Range (TRAC-WSMR) vignette used for the FCS Analysis of Alternatives (AoA) conducted in the Spring of 2003.[13] (Note: this Analysis of Alternatives vignette made the assumption that there was no Electronic Warfare (EW) played by the enemy. It was my intent to replicate this vignette as closely as possible in an agent-based model while assuming that EW can and will occur.) This thesis does not examine the directed task of analyzing individual communication system reliability due to model and time limitations.

In order to keep this thesis within the limits of what can reasonably be explored in the allotted time, the following research questions scope the direction of the research:

[13] Captain Matthew Mock (TRAC-WSMR), *Central Asia Vignettes (Vignette C4.1) FCS BN(-) attack vs. prepared Infantry defense Briefing*, Sent via email 3 December 2003.

- What characteristics of communications are imperative and at what levels are they significant for a combined arms battalion of the Army's Future Force employed in the attack?
- How do network latency, range, reliability, and throughput affect the Future Force's ability to fight and win decisively?
- How do network attacks (complete and partial degradation) and the Future Force's ability to respond to the attacks hamper fighting ability?
- If destroyed or hampered, which communication link(s) most affect the Future Force in terms of mission accomplishment?

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II. CASPIAN SEA ATTACK SCENARIO OVERVIEW

This chapter begins with a brief outline of the AoA process, followed by a discussion on the key weapon systems of both the Future Force and Red forces in the scenario. This is followed up with a thorough overview of the vignette used as the basis for the analysis. The intent is to leave the reader with an understanding of why the scenario was chosen as well as the advantages of using the scenario to evaluate the effects of communication on a battle outcome.

A. FCS ANALYSIS OF ALTERNATIVES PROCESS

TRAC—WSMR was the Army's lead agency for conducting the AoA of the FCS. This analysis took place over the course of eight months from May 2002 to January 2003 and compared the cost and operational effectiveness of the FCS UA to the alternatives. The purpose of this analysis was to provide senior decision makers with quantifiable comparisons between the current legacy forces, the intermediate forces being fielded and the new FCS scheduled to be fielded in the 2010 to 2014 timeframe. This AoA is required by DoD instruction and is intended to assist decision makers in selecting the most cost-effective materiel alternative to satisfy a mission need.[14]

The FCS AoA was a very broad-based and thorough analysis that covered several versions of the FCS employed in a variety of environments and mission sets. The two primary simulations used in the evaluation were CASTFOREM and JANUS.[15] Both of these models are stochastic, physics-based models that are widely accepted throughout the entire Department of Defense as a valid method for evaluating ground maneuver combat. Since the FCS, with its networked systems, fights very differently than current legacy forces, many of the traditional measures of effectiveness (e.g. force exchange ratios and loss exchange ratios) did not accurately measure "effectiveness." Thus, new measures of effectiveness were developed, such as: size of the area of operations controlled by a given element, time to complete the mission, kills at standoff

[14] Under Secretary of Defense for Acquisition, Technology and Logistics, *DoD Instruction 5000.2*, 12 May 2003, Retrieved 5 February 2004 from the World Wide Web at http://www.dtic.mil/whs/directives/corres/pdf2/i50002p.pdf.

[15] DMSO website, Retrieved 25 May, 2004 from the World Wide Web at https://www.dmso.mil/public/ .

(NLOS/BLOS vs. LOS), and acquiring and killing high payoff targets. Two of these measures are used for this subsequent analysis.

The results of the analysis showed that when the network performed as indicated, the FCS's enhanced situational awareness, agility, responsive and lethal fires put the new force at a significant advantage over legacy and interim forces. The capabilities of the FCS resulted in the ability to control a significantly larger AO with fewer committed forces in a shorter amount of time. One of the key factors they found was that enemy acquisitions occurred earlier in the FCS and enabled the commander to plan maneuver and effects before contact. As well, the FCS gained targetable (detect and classify) information about high payoff targets (HPT) earlier, allowing the commander to negate key enemy assets. Analysts, however were very aware that the network and C4ISR assets are now a very lucrative target for the enemy and further analysis was warranted, which led to the follow-on physics-based communications analysis that is ongoing.

B. FCS SYSTEMS DESCRIPTION

The FCS in its entirety consists of 24 major component platforms organized by function. These functions include LOS / BLOS weapon systems, NLOS weapon systems, C4ISR, Soldier and Support systems. All mounted systems have common attributes such as C-130 and C-17 aircraft transportability, add-on armor capable, and a common core chassis for reduced logistics burden. In addition, active protection systems, designed to intercept large caliber kinetic energy rounds come in various configurations for each of the FCS platforms to increase survivability despite the loss of heavy armor. This analysis employs and directly models 12 of these systems. To understand each of the platforms, a brief synopsis of purpose and capabilities for each modeled system is provided below. Each of these descriptions are extracted from the Army FCS UA Systems Book[16] used for all modeling to date.

1. Mounted Combat System (MCS)

The FCS manned combat platform that provides offensive maneuver to close with and destroy enemy forces is known as the MCS. It can most easily be compared to a legacy M1A series main battle tank. The MCS delivers precision fires at a rapid rate to

[16] US Army Materiel Systems Analysis Activity (US AMSAA), *Army Future Combat Systems Unit of Action Systems Book Version 3.0*, Aberdeen Proving Grounds, MD, 22 May 2003.

destroy multiple targets quickly. It fights differently than its legacy counterpart in that it maneuvers out of contact to positions of advantages and uses its superior precision fires to destroy enemy armor at standoff. Its increased mobility enables direct support to dismounted infantry in an assault, defeating bunkers and breaching walls during a tactical assault. Its main gun is a 120mm, direct fire, kinetic energy weapon with a basic load of 43 rounds. The MCS also comes equipped with a mix of the MK-19 40-mm automatic grenade launcher or the M2, 0.50 caliber machine gun as its close support weapon. It has the capability to target enemy Main Battle Tanks, light armor, artillery, and air defenses from 2-12 kilometers using both organic and inorganic sensing abilities.

2. Infantry Carrier Vehicle (ICV)

The FCS manned combat platform that provides the mobility for 11 personnel (two-man crew and nine-man infantry squad) on the battlefield is known as the ICV. The nearest legacy comparison to the ICV is the M-2 Bradley Fighting Vehicle. This asset is commanded by the infantry platoons and companies within the combined arms battalion and delivers dismounted forces to the close battle. In addition, the ICV supports the squad by providing self-defense weapons support and carries the majority of the squad's equipment, freeing the individual soldier form being burdened with equipment. The ICV can also be reconfigured to carry two anti-tank guided missiles or to carry litter patients as a medical vehicle. The main close support weapon is the MK-44, 30mm chain gun that provides mobility or firepower kills to enemy light armor vehicles from 1500 to 2000 meters. Sensor capability for the ICV varies dependent on configuration, but is designed primarily to identify and classify LOS targets.

3. Armed Robotic Vehicle Assault Variant (ARV-A)

The FCS unmanned system configured for support of dismounted infantry in the assault is known as the ARV-A. Externally transportable in an operational configuration by utility helicopters, the ARV-A remotely provides reconnaissance capability in military operations in urbanized terrain (MOUT) and other battlespaces. Its primary use is in support to the dismounted infantry with its direct fire and AT weapons. It possesses the ability to remotely deploy unmanned sensors, remotely locate or by-pass threat obstacles in buildings, bunkers and tunnels. A secondary mission is to remotely assess BDA and provide a communications retrans node as required. When employed, the ARV-A has the capability to be operated semi-autonomously (manual initial program of routes, autonomous thereafter) in rolling open terrain or manually operated by video feed. The

ARV-A comes equipped with three Javelin ATGMs designed to engage MBTs at zero to five km. In addition, it possesses close support / suppressive fire ability provided by the M-240B 7.62mm machine gun.

4. Armed Robotic Vehicle — Reconnaissance Surveillance, and Target Acquisition Variant (ARV-RSTA)

The FCS system that is designed to provide remote reconnaissance capability in MOUT and other battlespaces is known as the ARV-RSTA. As with all unmanned systems, the overwhelming goal of the system is to provide information about the area of operations without placing manned systems in harms way. The nature of this unmanned system allows the commander the flexibility to employ it in an atypical manner to confuse and deceive the enemy while "flushing" them out. The primary purpose of this vehicle is to remotely deploy sensors, identify threat obstacles and identify bypass areas in buildings, tunnels, bunkers, and other urban features to provide enhanced situational awareness to the maneuver unit. Secondary purposes of this platform are to provide a communications relay as well as provide remote BDA. This platform employs the M-230, 30mm chain gun as its defensive weapon system.

5. Non-Line-of-Sight Mortar (NLOS Mortar)

The NLOS Mortar is a manned mobile platform that provides short range indirect fires in support of assault battle units. The weapon is mounted on the common core FCS chassis and provides responsive indirect fires (8 to 10 rounds per minute) with its 120mm smooth bore mortar tube. The key to this system lies in its ability to provide fire support out to 12 to 15 kilometers, significantly improving on modern mortar fire support. The system is employed in a Combined Arms Battalion, allowing the commander organic fire support, facilitating responsiveness. The NLOS Mortar also comes with either a 0.50 caliber machine gun or a MK-19 grenade launcher as its close support weapon.

6. Non-Line-of-Sight Launch System (NLOS LS)

The NLOS LS is the FCS platform which provides networked, extended-range targeting and precision attack of armored, lightly armored, and other stationary and moving targets. The system's primary purpose is to provide responsive precision attack of HPTs in support of the UA. This platform can most easily be compared with M-270 MLRS — Multiple Launch Rocket Systems which are in the army inventory today. The significant differences between the MLRS and NLOS LS are in the munitions available and the fire control system. NLOS LS has a variety of improved munitions available such as loitering missiles which fly over a designated target area until a target presents itself (up to 30 minute loiter time). The fire control system is enhanced to allow in-flight targeting updates of moving targets. Precision munitions are designed to operate out to 40-60 kilometers, allowing attrition of key enemy mounted systems without committing dismounted or LOS units.

7. Non-Line-of-Sight Cannon (NLOS Cannon)

The NLOS Cannon is the FCS manned combat platform that provides networked, extended range targeting and precision attack of point and area targets in support of the UA. This system is most easily compared with the M-109/A6 Paladin self propelled howitzer which is in the army inventory today. The significant difference between the current system and the NLOS Cannon lies in the fire control system. The improved fire control system enhances responsiveness by providing fires within 15 seconds and firing 6-10 rounds per minute at a range of 30-40 kilometers. The NLOS Cannon is employed at the UA level in support of a Combined Arms Battalion. The platform also possesses self defense capability through its 0.50 caliber machine gun or MK-19 grenade launcher.

8. Reconnaissance and Surveillance Vehicle (R&SV)

The heart of the "hunter" systems in the FCS is the R&SV. This platform provides streamlined acquisition, discrimination of multiple target sets using its onboard sensor systems. The sensors are designed to detect, locate, track, classify and automatically identify targets from increased standoff ranges under all climatic conditions during both day and night operations. Key to the advanced sensors is the ability of the R&SV to communicate its information to "killer" systems such as the various NLOS systems through its robust communication abilities. The platform comes equipped with either a 0.50 caliber machine gun or the MK-19 grenade launcher as its close support weapon.

9. Unmanned Aerial Vehicle — Class I, II, and III (UAV - CL I, II, III)

The FCS hosts a variety of UAVs designed to provide capability for RSTA operations in open, rolling, complex, and urban terrain, under canopy, and in MOUT environments. The Class I and II UAVs are vertical take off and landing platforms that are organic to the platoon and company levels respectively. Both platforms have various sensor configurations available (e.g. thermal, enhanced optical imagery and radar) to provide the pertinent information desired by the unit depending on the operational environment. The Class III UAV is a fixed wing aircraft capable of providing similar capabilities to the Class I and II UAVs, however, with increased endurance and additional features such as chemical, biological, radiological and nuclear detection and enhanced sensors. The Class III UAV is employed at the battalion level. All three UAVs possess significant communication ability to provide retrans and real-time targeting information to other FCS "killer" systems. The primary purpose of all UAVs available to the FCS is to reduce operational and tactical risks associated with small unit operations by providing early warning and targeting information without committing manned assets.

10. Land Warrior Future Combat System (LW-FCS)

The LW integrates small arms with high-tech equipment, enabling ground forces to deploy, fight and win on the future battlefield. Land Warrior looks at the soldier as a complete weapon system in comparison with the "legacy" mindset that the soldier was a component of a given weapon system. Land Warrior consists of three main thrusts: lethality, survivability, and command and control. Key to the integration of these thrusts is incorporating these functions with the uniform that the soldier wears. Land Warrior has five subsystems: the weapon, integrated helmet assembly, protective clothing and individual equipment, computer/radio, and software.

C. RED FORCE SYSTEMS DESCRIPTION

The Red force pitted against the FCS used in this analysis resembles a company sized element of the modern day Russian Motorized Rifle Battalion. All enemy systems descriptions are extracted from the Jane's Information Group website[17], an unclassified, yet well respected source commonly used in analysis of this type. Examples abound

[17] David C. Isby, *Organization of the Russian Motor Rifle Battalion*, in Jane's Intelligence Review [online journal] (volume 007/001, 1995 [cited 29 April 2004]); Retrieved 5 January 2004 from the World Wide Web at http://www4.janes.com .

where Jane's is used for development of force structure such as the paper entitled "Objective Force Urban Operations Agent-Based Simulation Experiment" by Lloyd Brown and Thomas Cioppa.[18]

The MRB company consists of approximately 104 personnel (primarily dismounted aided by mounted systems). While, in all, the MRB has 22 major weapon systems in its inventory, this analysis focuses on the modeling of only eight systems. While significant effort was exerted to ensure the same level of detail in the modeling of the Red force weapon systems, the characteristics of each system will only be briefly outlined in Table 1.

System Description	Major System Characteristics
BMP-3	2A-42 / 30mm Machine Gun (200 rounds per minute, 4000 meter range)
82mm Mortar	Smooth bore mortar (8-10 rounds per minute, 4000 meter range)
SA-16 – MANPAD	Man Portable Air Defense System (2 minute acquisition / firing time with range up to 5000 meters)
RPG-7	Rocket Propelled Grenade - short range (100meters) with reloadable warheads
AT-7	Anti-tank guided missile (1500 meter firing range)
RPK-74	5.45 mm light machine gun (50 rounds per minute at 460 meter maximum effective range)
AK-M	7.62 mm sub machine gun (15 rounds per minute at 400 meter maximum effective range)
SVD	7.62mm Sniper Rifle (1000 meter maximum effective range)

Table 1. Description of Major Red Force Weapon Systems

[18] Brown, Major Lloyd and Lieutenant Colonel Thomas Cioppa, *Objective Force Urban Operations Agent-based Simulation Experiment*, US Army TRADOC Analysis Center Technical Document TRAC-M-TR-03-021, Naval Postgraduate School, Monterey, CA 93943, June 2003.

D. MODEL VIGNETTE DESCRIPTION

This analysis focuses on a UA Combined Arms Battalion employed in the attack against a company sized enemy. The scenario we use is derived from analysis conducted by TRAC-WSMR during the Analysis of Alternative of the FCS during summer 2002.[19]

The scenario was originally conducted in JANUS with the main purpose of analyzing weapon system effectiveness between the three options examined in the AoA. Understanding the main goal of the original analysis is key, since TRAC-WSMR's focus was not on how various communications environments might affect a battle.

The vignette takes place in what the FCS considers "complex terrain." In general terms, this type of terrain is described by limited avenues of approach with fast changing relief, such as mountainous terrain. The actual location is in the Caspian Sea area, specifically the country of Azerbaijan. While the specific location holds only limited pertinence to current military operations, the terrain set holds several beneficial aspects when evaluating the FCS. Such benefits are that the diverse terrain taxes the mobility and agility of the FCS. With a limited road network, limited infrastructure, and steep, mountainous terrain, the FCS is placed in a difficult scenario which it must overcome. The advanced guided munitions from the NLOS systems are suited for overcoming some of the mobility shortfalls, but rely upon the advanced sensors to feed the operational picture. In addition, the terrain set exercises the relatively new concept of BLOS, that is, using networked overhead sensors to extend the line of sight of weapon systems that were typically known to be strictly LOS.

[19] US Army TRACOC Analysis Center, *Objective Force / Future Combat Systems Analysis of Alternatives Tactical-Level Force Effectiveness Analysis*, US Army TRADOC Analysis Center Technical Document TRAC-WSMR-SB-03-027-3, TRAC White Sands Missile Range, September 2003.

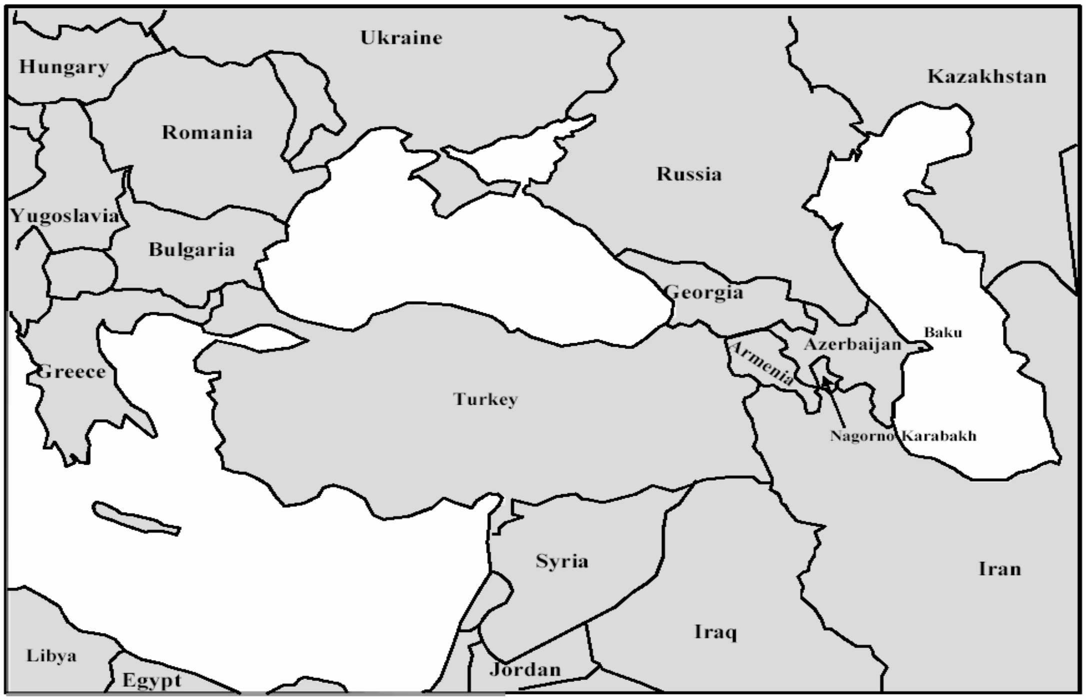
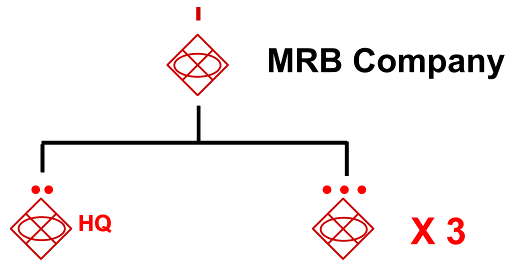


Figure 1. Caspian Sea Area of Operations

During the original analysis, this vignette assumed that the links between the FCS systems were 100 percent reachable and reliable with no enemy intervention. The term reachable and reliable is used in this context to describe the ability of the unit to communicate throughout the battlespace without having to worry about enemy interdiction or malfunction of any equipment. As has been alluded to previously, this concept could prove to be the largest challenge of the FCS and is the assumption that this analysis investigates.

The disposition of the enemy forces in this analysis is outlined in Figure 2. The Red forces are assumed to be at 100 percent strength and have the advantage of being in well fortified and prepared defensive positions. Extending this knowledge of fortified positions, an additional assumption was made that the Red forces are immune to any communications difficulties. This is not a far fetched assumption since with more time, many forms of redundant communications could be established, such as radio and satellite communications at the top of the technology spectrum or wire communications and couriers at the lower end.



1 IFV	3 IFV
1 ATGM dismounted	3 ATGM dismounted
4 82mm Mort	1 MANPAD
7 AK 47	3 RPG
14 Personnel	15 AK 47
	1 SVD Sniper Rifle
	3 RPK-74
	30 Personnel

Figure 2. Red Force Task Organization / Capabilities

The Red forces have intelligence to indicate that the FCS desires seizure of a key airfield in the area of operations, but is unaware of the time or precise location of advance. Given this situation, the Red force mission is to defend in order to deny FCS use of the airfield. To this end, it arrays forces in a decentralized area defense, occupying covered and concealed positions that overwatch the airfield and air corridors to the airfield.

The disposition of the Blue forces is outlined in Figure 4. The FCS Combined Arms Battalion has been outfitted with all of the organic assets the force is templated to have at fielding in 2012. The force structure has been tailored to the mission and assumes priority of a portion of two key UA supporting assets to include three NLOS LS and two NLOS Cannons with their associated sensing abilities (two CL III UAVs).

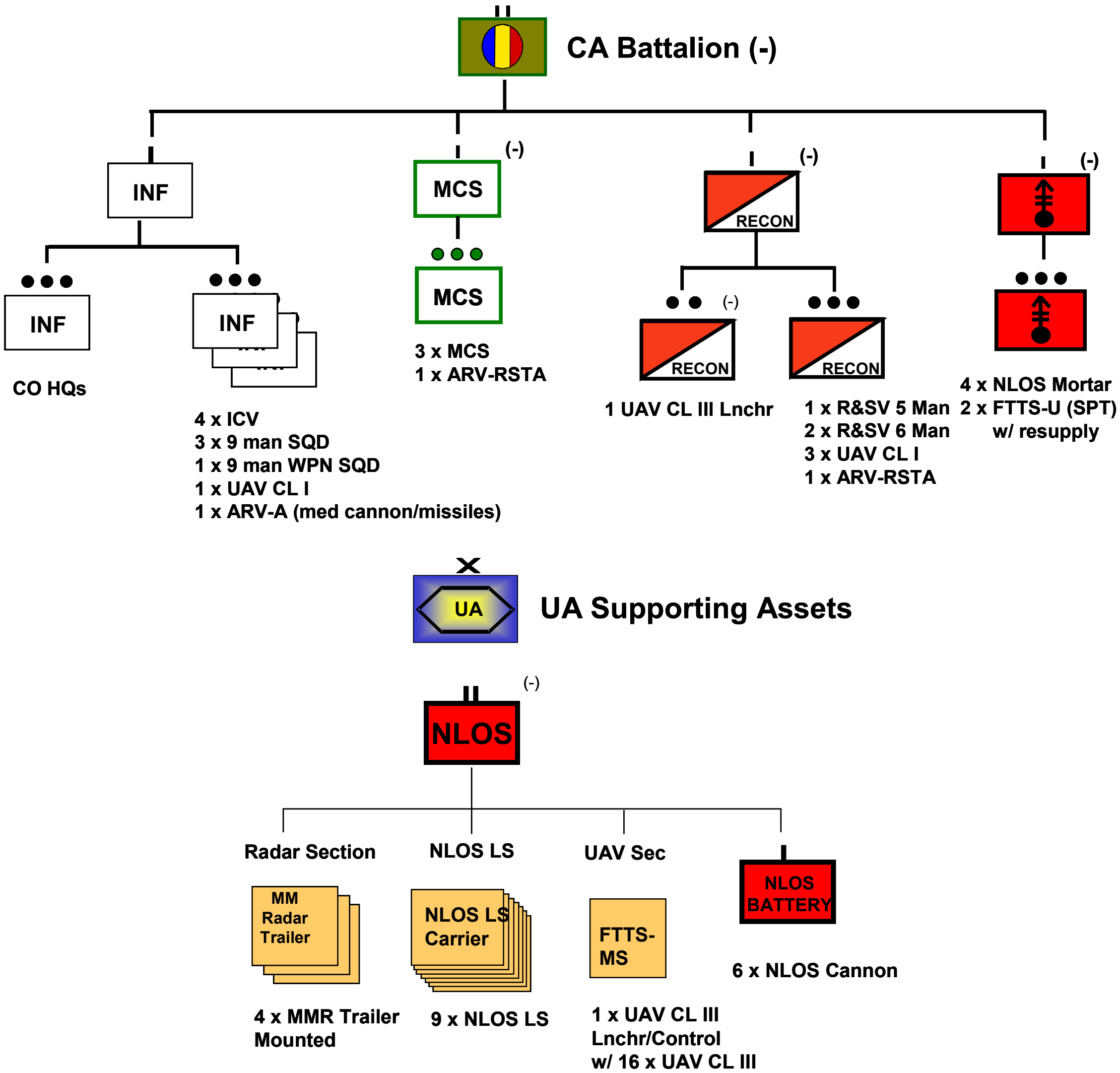


Figure 3. Blue Force Task Organization / Capabilities

The CA Battalion attack against the Red forces is a component of a larger UA mission that is to attack with three CA battalions within the area of operations to defeat enemy forces. The purpose of this attack is to secure use of the airfield to facilitate freedom of maneuver of follow-on forces. The concept of the UA mission is to attack objective FORD with 1st CA BN (the focus of this analysis) to secure the terrain influencing the airfield to provide secure air corridors for follow-on forces. The other two CA BNs will then attack to the south of the airfield to secure the southern corridor to the airfield. This general concept, with enemy templated defenses is depicted graphically in Figure 4 and is best when viewed in color.

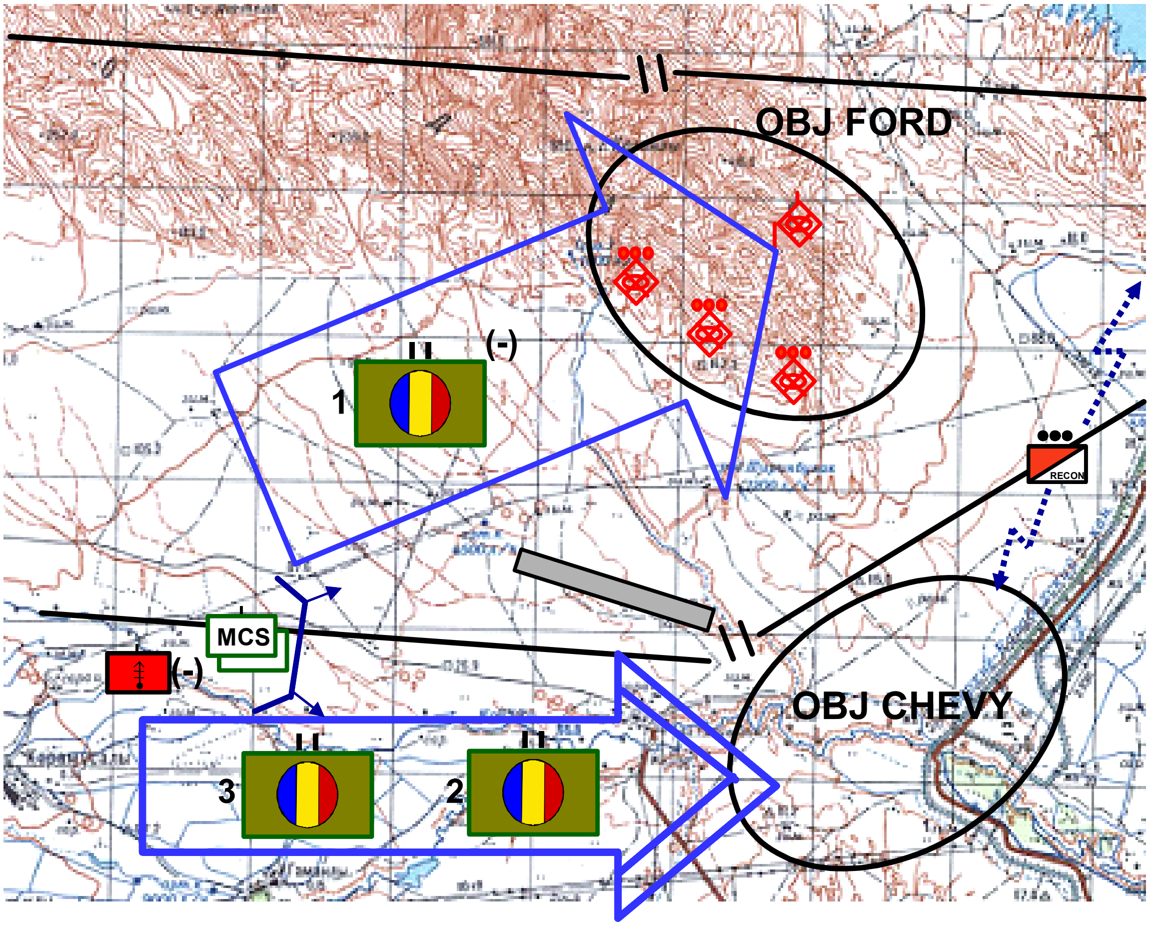


Figure 4. Graphical Depiction of UA Attack Mission

To detail the focus of this analysis a bit more, the 1st CA BN's attack concept in their area of operations is conducted in three phases. Phase 1 is known as the Reconnaissance and NLOS fight. This phase deploys reconnaissance assets (RS&V, UAVs) forward of the main fighting element (consisting of the MCS, IFVs and NLOS systems) and attrites the Red forces with NLOS systems. The goal of reconnaissance elements is to identify Red force obstacles and defensive positions and feed this information to indirect firing systems. Phase 2 is known as the LOS / BLOS fight. This phase deploys MCS assets forward to establish support by fire positions outside of enemy AT systems range to provide BLOS fires destroying enemy infantry fighting vehicles in zone. ICV platoons then attack along AXIS LEG to destroy defending forces. Infantry platoons dismount in the vicinity of CP D and maneuver ICVs to positions to support with MK-44 weapons. Phase 3 is known as the consolidation and reorganization phase and secures the terrain overlooking the airfield. In addition, 1st CA BN establishes a hasty defense in preparation for any Red force counterattack. This detailed concept is depicted graphically in Figure 5, and is best when viewed in color.

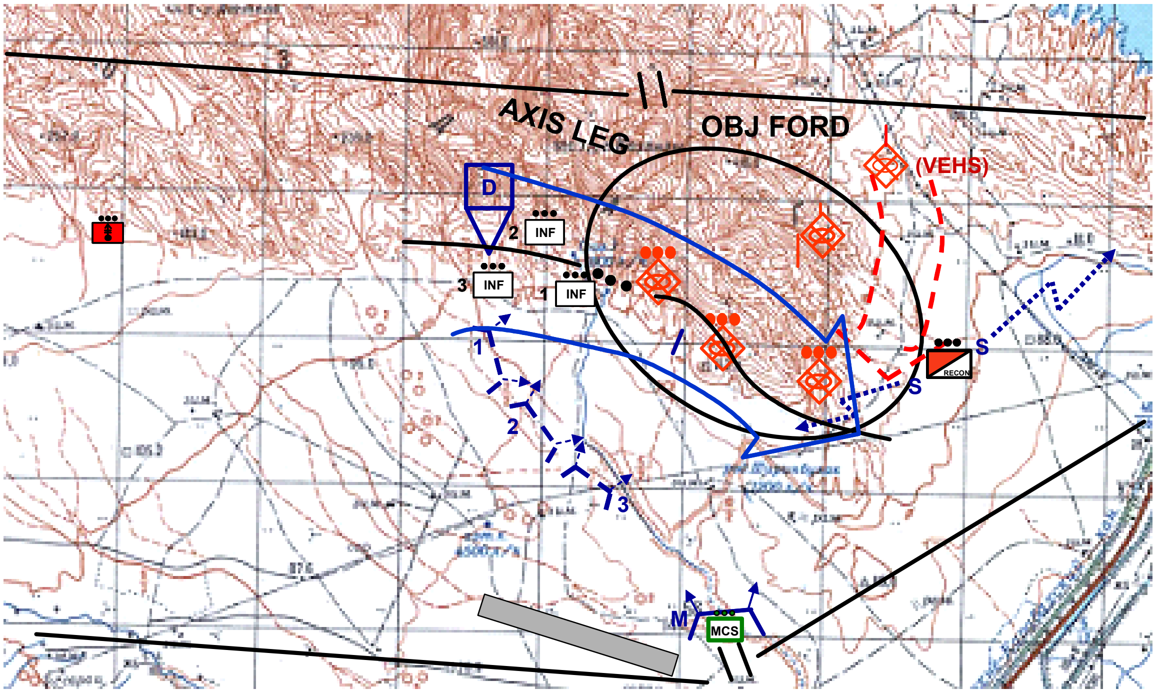


Figure 5. Graphical Depiction of 1st CA BN's Attack Mission

In accordance with most deliberate military planning, the indirect fires have been prioritized by firing system and associated priority targeting. This attack guidance matrix is shown in Table 2. This guidance will provide a basis for modeling assumptions used in the simulation of this vignette and are described later in subsequent chapters.

System	Targets
NLOS L/S	IFVs
	C2
	ADA
NLOS 155	Mortars
	IN (Squad or greater)
	AT
	ADA (Manpad)
HIMARS	Artillery
	ADA
	Radar
	IN (PLT or greater)
NLOS Mort	IN (crew serve WPNs)
	Mortars
	Infantry
	AT
MCS	ICV

Table 2. NLOS / BLOS Attack Guidance Matrix

Now, with an understanding of the scenario being used, a thorough discussion of the model follows. In addition, a detailed description of the methods used to replicate behaviors and characteristics of the various weapon systems is included.

III. MODEL DEVELOPMENT

Anything but war is simulation

General Paul Gorman USA Retired

This chapter begins with a brief discussion of simulation models in general and follows up with a description of Agent-Based Models (ABMs) and their place in combat modeling. As the workhorse of this analysis, the chapter also discusses MANA, the ABM chosen for this problem. The bulk of this chapter is dedicated to how agents and behaviors are modeled in MANA. The chapter concludes with a description of shortcomings and "bugs" encountered during the course of the analysis. The intent is to leave the reader with some degree of confidence that the model is reasonable for the scenario chosen and that parameters have a basis with physical characteristics of the system modeled.

A. ABM OVERVIEW

The U.S. DoD uses simulation models to support its decision making process. As defined by the Defense Modeling and Simulation Office in its vision statement,[20] defense modeling and simulation provides readily available, operationally valid tools for use by DoD components for two main purposes:

- To train jointly, develop doctrine and tactics, formulate operational plans, and assess war fighting situations.
- To support technology assessment, system upgrade, prototype and full scale development, and force structuring.

Even if significant resources were available and it was permissible to pit forces against each other using real weapons to validate doctrine and tactics, many uncertainties would still exist. It could be said that for every situation tested, there would be infinitely many variants of environmental conditions, enemy courses of action, and other intangibles that the fog of war bring out.

[20] DMSO vision statement, Retrieved 5 May 2004 from the World Wide Web at https://www.dmso.mil/public/vision .

With this said, the DoD relies on modeling and simulation to capture insights and enable prudent decision making. Simulation experiments can allow decision makers to test or train in conditions that would normally not be feasible due to safety, resource, or security restrictions. At the core of these experiments are many physics-based models which attempt to replicate the *physical effects* of a certain action. A round discharged from a weapon can be described with a high level of fidelity using well established laws of physics taking into account the velocity of the round, wind, atmospheric media, etc. Often these laws, however, require many input variables to accurately predict the location of impact or the force at which it impacts. These high-resolution simulations are often complex and resource intensive. A simulation which may have thousands of rounds fired from thousands of battlefield entities requires significant computing ability to provide the insights required for prudent decision making.

Another approach to modeling these experiments is to attempt to replicate the *behaviors* of a certain battlefield action. Using the discharged round example provided above, one could observe that a round when fired from a weapon at a given distance has an estimated probability of hitting its intended target. Further, it can be observed that certain rounds will be effective against certain targets and vice versa. ABMs seek to employ a "small" set of rules with which simulation entities known as *agents* react to stimulus.

ABMs have developed to a degree such that they are appropriate for exploring small scenarios which are termed distillations. Distillations are relatively small and simple scenarios that attempt to capture only the essence of a situation without trying to model all of the details that could be considered.[21] Surely these models do not replicate all of the physical aspects of a certain situation, but they can provide significant insights to emergent behaviors as a result of variations in the rule set.

ABMs are characterized by quick scenario set up and fast run times. This allows the analyst to rapidly consider many alternatives. This exploratory analysis approach attempts to help people think through complicated issues by illuminating the consequences of various assumptions, reinforcing or challenging intuition and illustrating

[21] Brown, p. 3.

alternatives that might have been overlooked. This leads to the process of identifying regions, ranges, and thresholds where interesting things happen rather than predicting, optimizing, or tuning.[22] To be clear, ABMs are not designed to take the place of detailed, physics-based models, but are designed to augment these models by permitting users to examine the problem at hand over a much broader range of possibilities. These fast running models can be used as screening tools during problem formulation to scan the problem space, allowing identification of areas of concern for deeper analysis by physics-based models.[23]

Models are for thinking

Sir Maurice Kendall

B. ENTER MANA

Much of the information presented in this section is taken primarily from the MANA User's Manual.[24] Map Aware Non-Uniform Automata (MANA) was developed by New Zeland's Defense Technology Agency (DTA). In the spirit of the previous discussion about ABMs, MANA stands for:

- Map Aware — Agents are aware of and respond to, not only their local surroundings and terrain, but also a collective registry of recorded battlefield activities.
- Non-Uniform — Not all agents move and behave in the same way (much like soldiers, sailors or airmen.)
- Automata — Agents can react independently to events, using their own "personalities." Personalities, in general, are propensities that guide an agent's actions to move.

MANA was designed for use as a scenario-exploring model to address a broad range of problems. The model is not intended to be able to describe every aspect of a

[22] Lucas, Tom, Susan Sanchez, Major Lloyd Brown, William Vinyard, *Better Designs for High Dimensional Explorations of Distillations*, Maneuver Warfare Science 2002, edited by Gary Horne and Sarah Johnson, 2002.

[23] Brown, p. 6.

[24] Galligan, David P., Mark A. Anderson, Michael K. Lauren, *Map Aware, Non-Uniform Automata version 3.0*, New Zeland Defense Technology, February 2004.

military operation. Furthermore, there is no built in "intelligence" which determines the plan that entities are working with. As a result, agents do not always behave in a sensible manner and are capable of making what could be viewed as "mistakes." The developers give this caution and response:

> [C]areful thought must be given when setting up a scenario. There must be a clear idea of which aspect of warfare the scenario is addressing, and what the entities are trying to do. Though such an approach may seem pre-potted, the non-linear nature of the model ensures that, regardless of the modeller's preconception, a startlingly large number of outcomes are possible. Such a range of outcomes is characteristic of complex adaptive systems, and occurs even with quite simple rules of behavior. This is the essence of what we are trying to do: explore the greatest range of possible outcomes with the least set-up time. Since it is only necessary to have simple behavioral rules to achieve this, it seems almost pointless to make the rules more complicated than necessary.[25]

The ability to take a rough problem, develop a scenario, and implement this scenario in short order with nothing more than a user's manual and a standard performance personal computer made the choice of MANA as the platform for analysis simple. MANA is designed around a well developed Graphical User Interface (GUI) which facilitates quick scenario setup and is well documented with many built in tutorial simulations. Within just a couple of hours, a user can have a general understanding of how the model works and be on their way to tackling the problem at hand.

C. BEHAVIOR MODELING

1. Creating the Battlefield

This section focuses on how agents were created in MANA. Careful attention is devoted to showing screen shots to facilitate understanding of the model. While the intent is to leave the reader with an understanding of the workings of the model, unresolved questions concerning model operation should be directed to the MANA Users Manual.

The first step taken in this analysis was to get a handle on the physical characteristics of what is trying to be modeled. Chapter 2 discussed some of the physical characteristics of the forces and platforms employed in the attack / defend scenario. One may observe that each platform has certain attributes such as the ability to sense,

[25] Galligan, p. 7.

communicate, move and shoot. Of course, each platform has varying degrees to which it can do this, but these physical characteristics are the bedrock of behavior modeling. To facilitate this process of converting physical characteristics to model parameters, a spreadsheet was created. An excerpt from this spreadsheet is shown in Table 3.

			NLOS-Mortar
Lethality			
	Pri - weapons		120mm B/LOS
	Unguided	Fire Rate (L) - RPM	8
		Fire Rage (H) - RPM	10
		Range (L) - meters	
		Range (H) - meters	1000
		Basic Load - rounds	65
	Guided	Fire Rate (L) - RPM	8
		Fire Rage (H) - RPM	10
		Range (L) - meters	12000
		Range (H) - meters	15000
		Basic Load- rounds	65
		Lethal Radius - meters	60
	Type CSW		
		M2 / MK 44*	1
		Mk-19 / XM 307 *	1
		M240B	
		CE APS	
		Mk-44	
		Stinger/Dis	
		Javelin/Dis	
Survivability			
	Ballistic protection		AT-M
	Employ Obscurants		X
	Mine Detection		X
	Obs/Mine Destruction		
	Obs/Mine marking		X
Mobility			
	Speed		
		Hard surf	90
		x-cntry - kph	50
		dash	0-48/ 8s
Sensing	Type		Radar Plus

Table 3. Real-World Weapon Characteristic Spreadsheet Excerpt

This spreadsheet serves as a single location to place major platform characteristics for conversion to model parameters. An entry for each major platform and close support weapon on both Blue and Red forces was completed. The example provided in Table 3 shows the weapon characteristics for the NLOS Mortar. The entire set of parameters for all weapon systems used in the analysis is given in Appendix A. It is noted that the entries match the brief platform description provided in Chapter II of this thesis and the descriptions provided in the Army Future Combat Systems Unit of Action Systems Book.

The next step in the process of conversion to model parameters was to create a battlefield in MANA. The battlefield in MANA is a rectangular grid that represents the battle space where agents interact. The battlefield determines the resolution at which model entities react. It has a map of the terrain and elevation of the area of interest based on a standard bitmap file. Figure 6 shows the MANA panel where the battlefield is defined. Two key things to note in Figure 6 are the *Number of Cells* and *Real World Range* blocks.

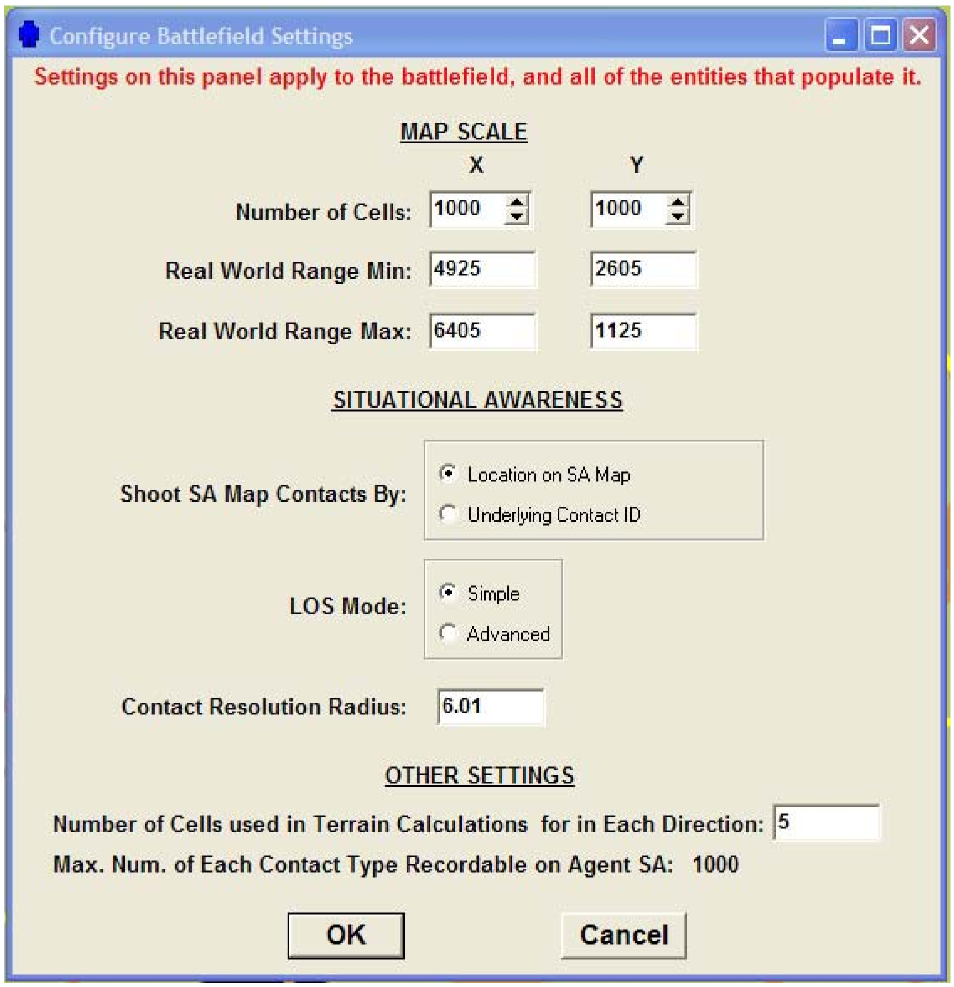


Figure 6. MANA Battlefield Definition Panel

The *Number of Cells* block allows the user to specify the model grid size (this ranges from a size of 50 to 1000.) Setting the number of cells to 1000 by 1000 ensures the maximum resolution of the model in terms of movement and other calculations. The *Number of Cells* is also key to converting real-world rates and distances to model parameters.

The *Real World Range* blocks facilitate placement of forces on the battlefield once map files are loaded into MANA. While these blocks are not necessary to ensure the proper functioning of the model, it allows the specification of the ranges in x and y directions represented by the model grid. For example, if using a standard military map (as is the case with this analysis), grid locations on the map are represented by an 8 digit grid coordinate. The first four digits represent the x location and the last 4 represent the y location. These *Real World Range* blocks allow the user to bring the world of "MANA pixels" to a physical location on the ground.

Once the MANA battlefield is defined, scenario maps can be loaded. There are three different maps that can be loaded into MANA: background, terrain, and elevation. The background map is not used by any algorithms in the model, but is used as a cosmetic enhancement for the scenario. A digital copy of the exact map in use for the tactical operation can be superimposed on the battlefield using the background map.

The terrain map captures the essential details of the battlespace for use in various algorithms in the model. MANA uses distinct colors to identify various terrain features. For example, the RGB color of 225,225,0 represents a road in MANA. A road has three attributes associated with it: going, cover and concealment. These attributes affect movement speed, kill probability and sensor detection of the agents in the model, respectively.

The final map that can be used in the model is the elevation map. As the title would indicate, this map contains information of the relief properties of the battlespace. Elevation maps are grey scale maps, ranging from white (highest point) to black (ground level). There are 256 possible levels of grey (0-255) to represent the heights used in line of sight calculations. By convention, MANA uses 10 times the grey scale color value to represent the real elevation. The elevation maps add realism to the model by preventing observation by agents obscured by a hill or major terrain.

Once the resolution of the battlefield is selected, physical weapon / platform characteristics can be converted into model parameters. In the scenario used in this analysis, it is noted that the real world battlespace occupies a 14.8 kilometer by 14.8 kilometer area. To ensure maximum resolution for movement computations, the MANA battlefield was set to a 1000 by 1000 pixel square. Using simple algebraic manipulation, one can find a conversion factor to take real world ranges and convert these into model parameters. The conversion factor for this scenario is shown below:

$$\frac{1000 \text{ pixels}}{14{,}800 \text{ meters}} = 14.8\frac{\text{meters}}{\text{pixel}}$$

For the NLOS mortar, the range of the weapon (as a MANA parameter), using this factor becomes:

$$\text{NLOS Mortar Range (in pixels)} = \frac{12{,}000 \text{ meters}}{14.8\frac{\text{meters}}{\text{pixel}}} = 810.8 \text{ pixels}$$

Rates, such as speed of movement, are computed similarly, however, the user must specify a resolution of time. In other words, the user must determine how many real world time units correspond to model time steps. For this scenario, the time resolution was set at 1 minute to 15 time steps (or equivalently, 1 time step is 4 seconds). The movement speed of the NLOS Mortar is computed as follows:

$$\text{NLOS Speed}\left(\text{in } \frac{\text{pixels}}{\text{time step}}\right) = \left(90\frac{\text{km}}{\text{hr}}\right)\left(\frac{1 \text{ hour}}{60 \text{ min}}\right)\left(\frac{1 \text{ min}}{15 \text{ steps}}\right)\left(\frac{1 \text{ pixel}}{14.8 \text{ m}}\right)\left(\frac{1000 \text{ m}}{1 \text{ km}}\right) = 6.76\frac{\text{pixels}}{\text{time step}}$$

These computations for the NLOS Mortar are summarized in Table 4 and are listed for all systems in Appendix A.

	Four Digit Grid			
Conversion Computation	X1	X2	Difference in Meters	
for Model Parameters	4925	6405	14800	
	MANA Battlefield Size		Conversion Factor (Meters / Pixel)	
	1000	Square	14.8	
	Real Time	Mana Steps	Conversion Factor (Hr / Time Step)	
Time Conversion	1 min	15	0.00111	
			NLOS-Mortar	
Lethality				
	Pri - weapons		120mm B/LOS	
	Unguided	**Fire Rate (L) - RPS**	0.053	
		Fire Rage (H) - RPS	0.067	
		Range (L) - pixels		
		Range (H) - pixels	67.6	
		Basic Load - rounds	65.0	
	Guided	**Fire Rate (L) - RPS**	0.053	
		Fire Rage (H) - RPS	0.067	
		Range (L) - pixels	810.8	
		Range (H) - pixels	1013.5	
		Basic Load- rounds	65.0	
		Lethal Radius - pixels	4.1	
	Type CSW			
		M2 / MK 44*	1	
		Mk-19 / XM 307 *	1	
		M240B		
		CE APS		
		Mk-44		
		Stinger/Dis		
		Javelin/Dis		
Survivability				
	Ballistic protection		AT-M	
	Employ Obscurants		X	
	Mine Detection		X	
	Obs/Mine Destruction			
	Obs/Mine marking		X	
Mobility				
	Speed			
		Hard surf	6.76	
		x-cntry - pix/ts	3.75	
		dash	0-48/ 8s	
Sensing	**Type**		**Radar Plus**	

Table 4. NLOS Mortar MANA Adjusted Parameters

2. Creating the Agents

The previous section identified the method of computing MANA agent parameters. Using a spreadsheet, it becomes a near trivial task to extend this to all platforms modeled once the real world data has been accessed. This section focuses on creating the model agents. In the MANA GUI, the way to create these agents is through the Edit Squad Properties option located under the Setup menu. Once this option is opened, the user sees the screen shown in Figure 7. Of particular interest is the presence of nine tabs, each of which will be discussed in brief, but is left to the reader to consult the users manual if further questions arise concerning model operation.

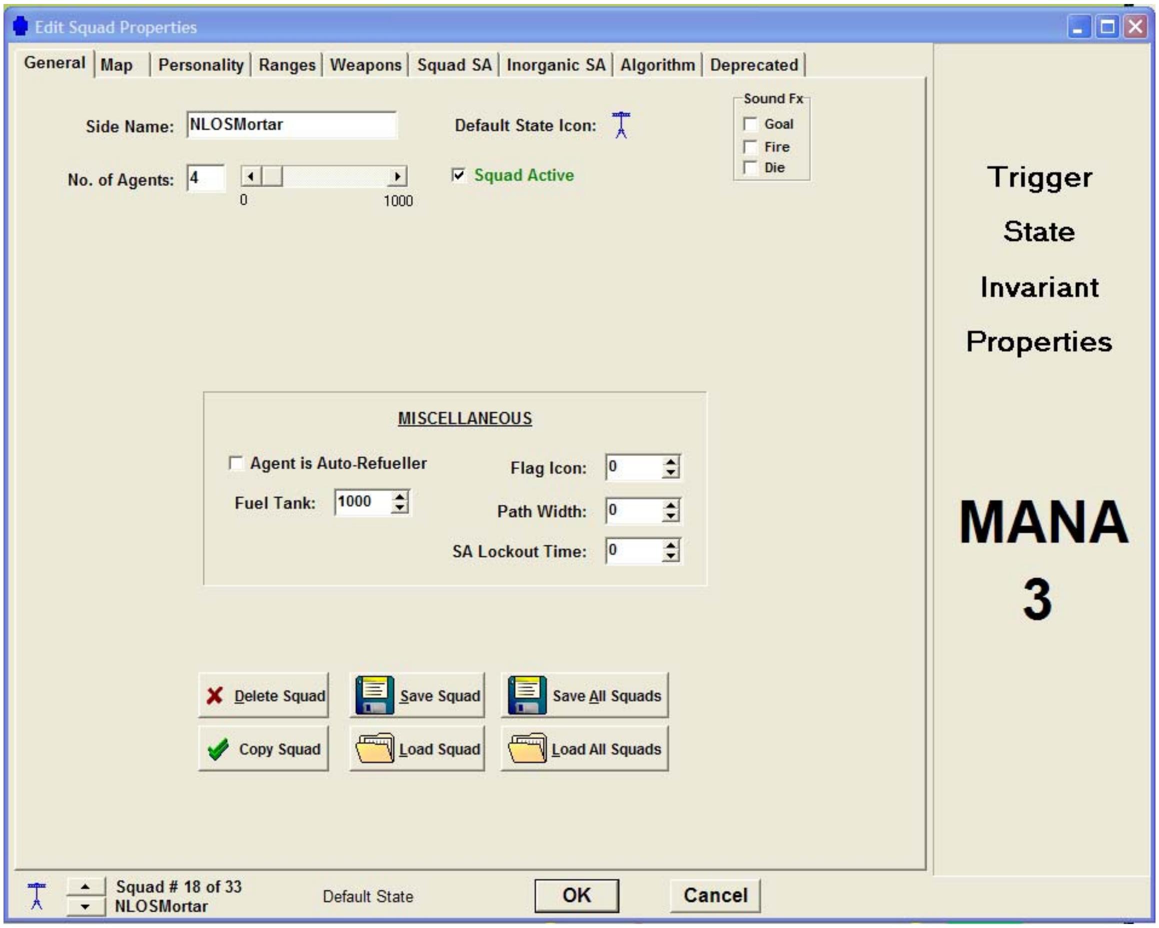


Figure 7. Edit Squad Properties Option (General Properties)

Each tab shows a screen divided up into two main portions common to all tabs: the settings section and a section for trigger state properties. Trigger state dependent settings allow the agents to change their decision process when user specified events occur. These include being shot at, taking a shot, reaching a waypoint, etc. The trigger state settings last for a user specified amount of time. These changes can be for individuals or for a whole squad at once.

The general tab allows the user to specify general properties for the agents in the squad, such as the number agents in the given squad as well the common name of the squad. The general tab does not allow for trigger state dependent settings as indicated by the panel on the right hand side.

The map tab gives initial direction to agents by establishing start points and waypoints to navigate towards. This allows the user to simulate general movement orders given to a subordinate unit for a given operation. The path specified may be adjusted by the agent during the simulation depending on its personality settings. By default, the final waypoint specified to a squad is its ultimate goal.

The personality tab is where the modeler can set personality weightings that drive agents toward or away from goals, friendly forces, or enemy forces. As indicated in Figure 8, these personality settings are trigger state dependent, allowing for more realistic modeling under various circumstances. Each personality setting ranges from -100 to 100, indicating the propensity of the agent to move toward (positive settings) or away from (negative settings) a particular battlefield object. The weighting factors can cause the entities to react to other entities, waypoints, terrain and information. As discussed in previous sections, the personality of an agent is one of the key features that ABDs, and MANA in particular, presents over physics-based models. The settings capture the “fog of war” and allow agents to make their own decisions, as opposed to the modeler explicitly determining their behavior in advance.

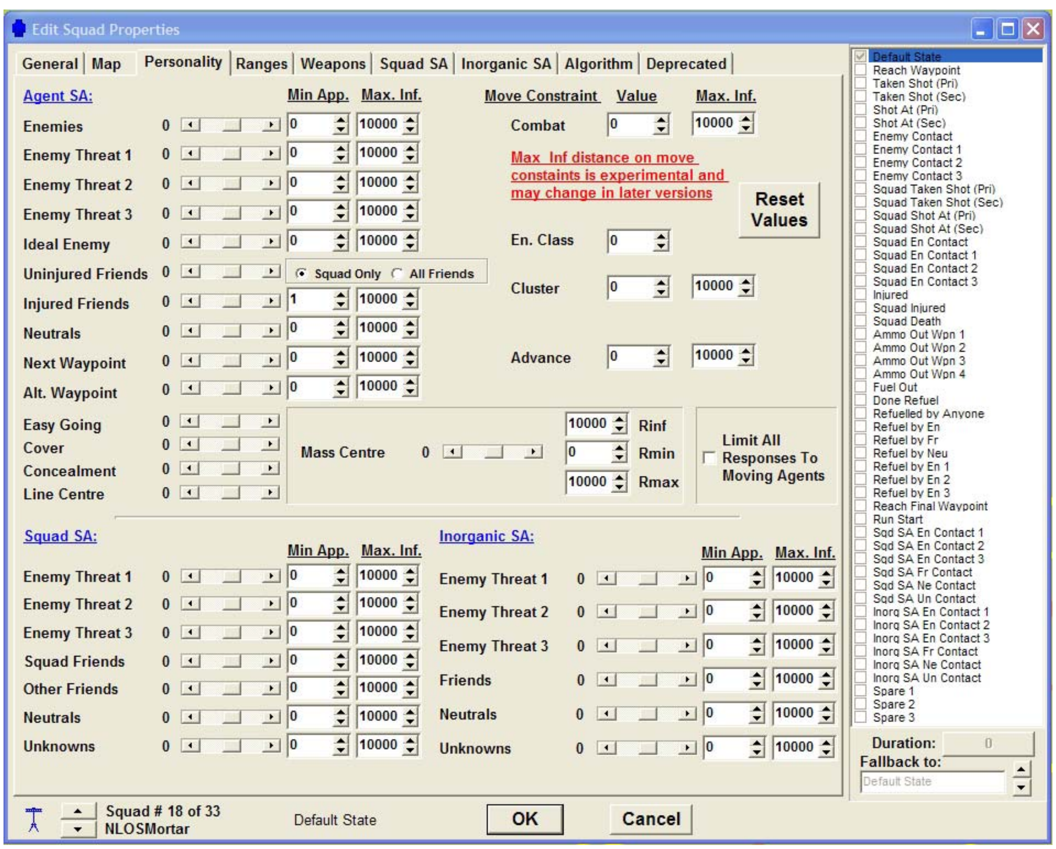


Figure 8. Edit Squad Properties Option (Personality Properties)

Since the focus of this analysis is not on the tactics of a certain operation, but on the communications aspects of combat, personalities in this scenario are only roughly modeled. Agents in this analysis have basic personality traits for when moving toward the objective, when agents come under fire, when they reach waypoints, and their final destination. These basic personalities are based on general observations from previous ABM FCS studies, such as that done by Lloyd Brown.[26]

The Ranges tab allows the modeler to specify key squad attributes such as movement speed (as described previously—in pixels per time step), allegiance of icons (friendly, enemy, or neutral), and sensing ability. To draw a comparison to modeling the behavior of a radar sensor, MANA does not try to replicate the propagation of a given radio wave throughout an atmospheric media as a physics-based model would. Instead, MANA allows the user to specify ranges and probabilities of detection and classification. While this is an abstraction to the way the sensor may physically operate, the author believes that this behavior may be modeled sufficiently to capture the broad effects of the sensor.

The weapons tab, as one might expect, describes weapon characteristics of the agents. Each agent has the ability to possess up to four weapons. These weapons are classified as direct or indirect fire (rifles or artillery pieces) and the manner in which they target their foe (using what they see, or using what their friends see). Contacts are represented by shapes which indicate the class of the contact. This notion of situational awareness is one of the key features of MANA and will be described later in this chapter. A sample situational awareness map is shown in Figure 9.

[26] Brown, Major Lloyd, "Military Operations in Urban Terrain Excursions and Analysis with Agent-based Models," Maneuver Warfare Science, USMC Project Albert Quantico, VA, 2003.

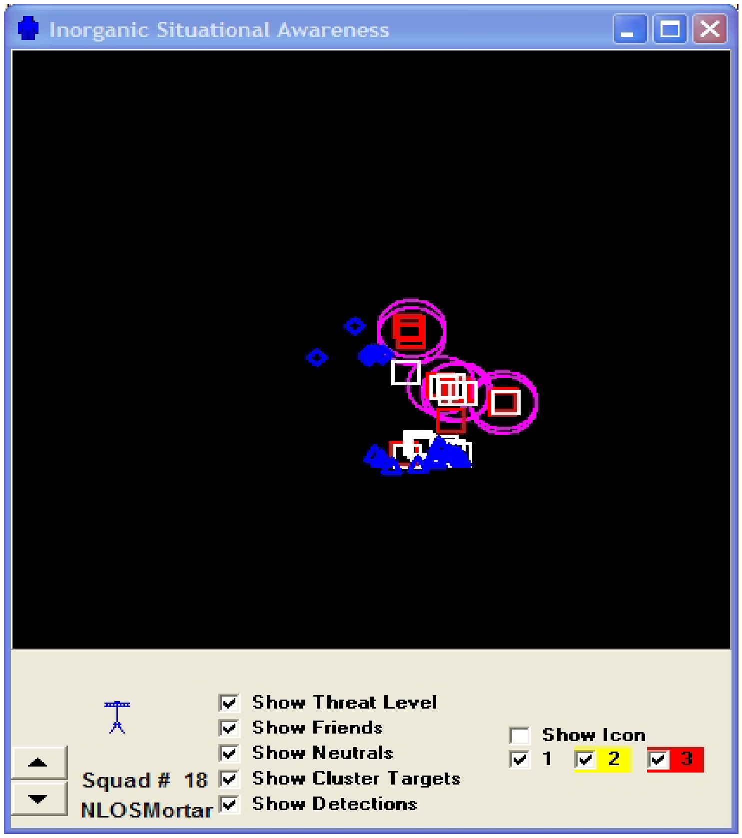


Figure 9. Sample Inorganic Situational Awareness Map (for NLOS Mortar)

Each weapon has “physical” characteristics such as the range and the rate that it may engage an enemy (as described previously—in pixels and rounds per time step, respectively). In order to accurately model the fact that the main gun on a tank would not, in reality, fire on a single infantry dismount, each weapon allows for the modeler to specify non-target classes.

Situational awareness comes in three distinct types in MANA, agent, squad, and inorganic. Agent situational awareness is nothing more than what an individual agent senses with organic sensors defined under the range tab. Squad situational awareness allows a given group of agents to share a “memory” of the locations of agents that have been detected in the form of a collective picture of sensor information. A low tech example of this awareness might be a soldier’s map board with templated enemy and friendly sightings. Squads who share information between one another allow for inorganic situational awareness. This inorganic situational awareness can be compared to networked communications between agents—the focus of this thesis. As expected, many of the parameters explored in this analysis are inorganic situational awareness parameters. The inorganic situational awareness tab is shown in Figure 10.

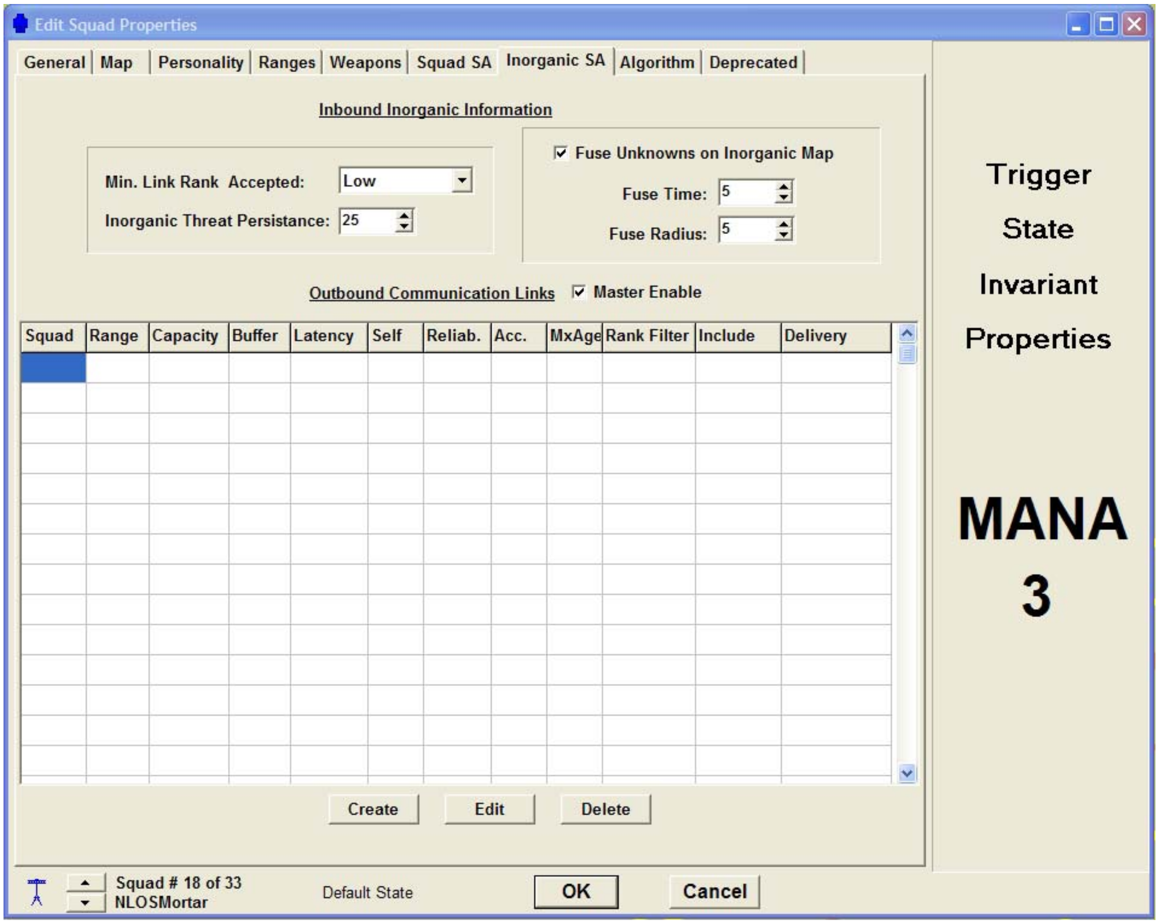


Figure 10. Edit Squad Properties Option (Inorganic SA Properties)

As indicated in Figure 10, there are 11 different communication properties that exist for every communication link. Some of the parameters are self explanatory, such as range and reliability. Each of these parameters may be set to specific values or, as is the case in this analysis, dynamically varied over realistic settings (best case, worst case and cases in between). Parameters that may not be entirely clear as to what they model are discussed below:

- Capacity — refers to the throughput of the communication link—this may be thought of as bandwidth or how quick messages may be sent.

- Buffer — refers to the number of messages that may be queued prior to sending. This replicates possible hardware constraints that may be present in a given network.

- Latency — this refers to how long it takes a given message to arrive at its intended recipient. Delays may be likened to routing issues in a given network.

- Reliability — this represents the likelihood that a given message will be successfully sent.

- Accuracy — Indicates the probability that a message sent is received correctly by its recipient. If the message is not received correctly, the message is classified as an unknown entity detection.

- Max Age — Acts as a filter to ensure that stale information does not clog a given communication link.

- Delivery — This discusses the protocol that the network employs. There are two options — send once or send until received.

The algorithm tab is used to change some of the movement algorithm options. The parameters on this panel are trigger state invariant. MANA employs three different algorithms which set the basic rules for agent movement. Each of the algorithms are similar in that they select the grid square within a agents movement range that most satisfies its desire to move towards some entities and away from others (as defined in the personality tab). The algorithm assigns a "penalty" for moving in a particular direction and the direction which provides the least "penalty" is selected. If several moves have a similarly low penalty, a move is chosen at random form those in the good set. All movements in this analysis utilize the Stephen Algorithm (see MANA users manual for more details on this algorithm).

Other movement settings can be specified in this tab to more closely replicate the behavior desired. Such settings include the ability to have a squad move together. This ensures that the fractional movement for each squad member is the same at each time step. The user can think of this as a parameter to represent squad cohesion. The ability to have terrain and elevation affect the movement speed is captured by selecting the going affects speed block. For most ground based agents, selecting this option makes sense since vehicles, in real life, will not traverse through impassible terrain. Air based agents such as UAVs make a case for unselecting this option. In other words, the speed at which a UAV moves is not hampered by impassible ground terrain.

The deprecated tab contains parameters which are now obsolete in the version of MANA used in this analysis. The developers of the model have chosen to keep this tab to ensure compatibility with previous versions.

Once all battlefield agents were created using the ideas presented above, the final appearance of the battlefield is as depicted in Figure 11 (best when viewed in color). This figure can be compared with Figure 5 which indicated the tactical concept that was presented with no specific simulation model in mind. The reader notes the enemy positions occupying the high ground overlooking the airfield, and the Blue forces poised to begin movement to the attack. The agents depicted to the far left represent the NLOS systems (mortars, cannons and launch systems). The Blue agents positioned closest to the Red forces are the RSV assets conducting reconnaissance forward of the main effort.

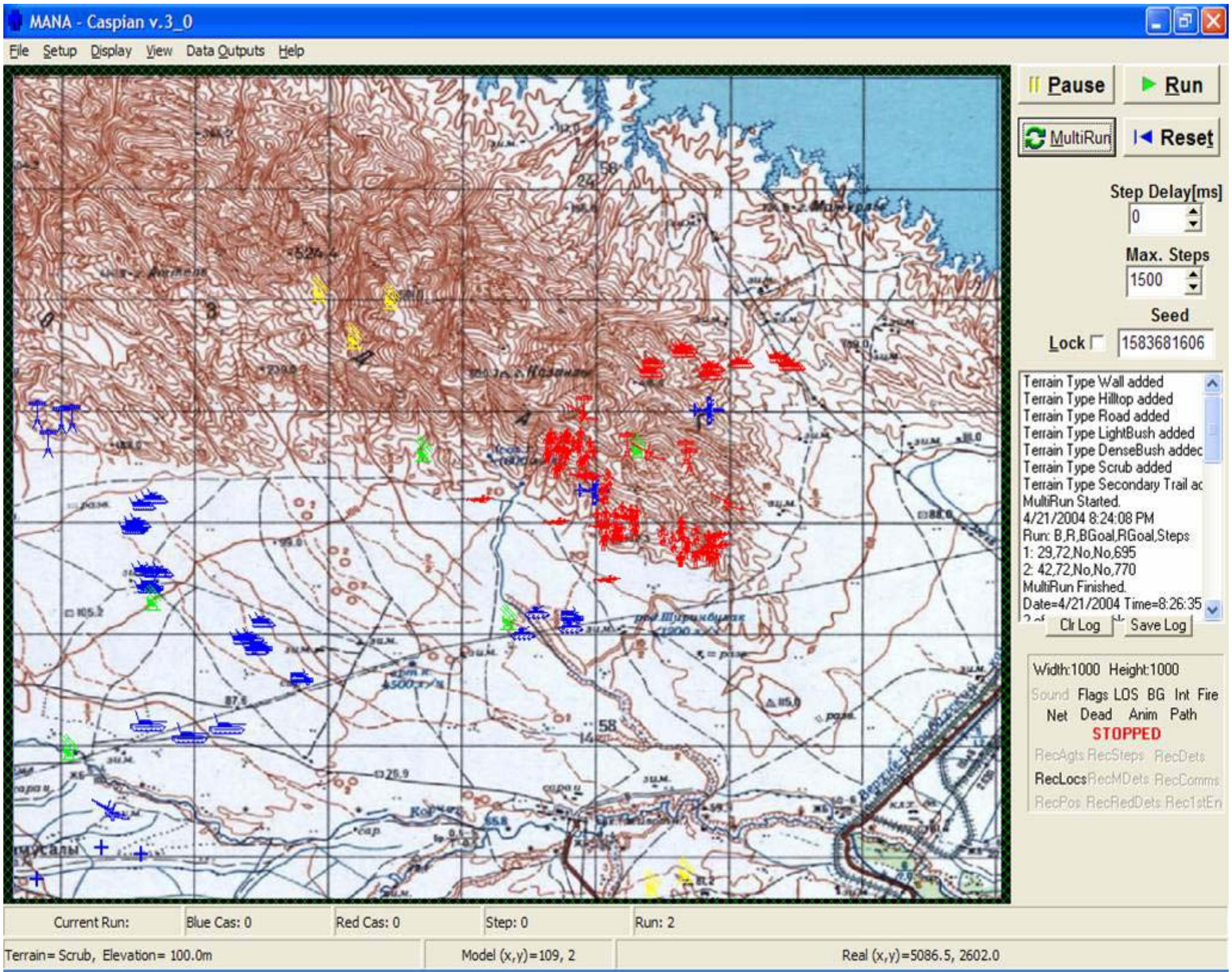


Figure 11. MANA Battlefield with all Agents Modeled

The final key portion of the model to be discussed is the ability of the modeler to establish stopping conditions. This is useful for modeling when a particular battle "should" end. Stop conditions allow the model to terminate a run when certain criteria are reached. This is useful to reduce computation time, or to record the run (battle) length as a measure of effectiveness (MOE). This parameter is used in this analysis to establish breakpoints for which Blue and Red forces will break contact, or withdraw. The conditions that may be selected are summarized in Figure 12.

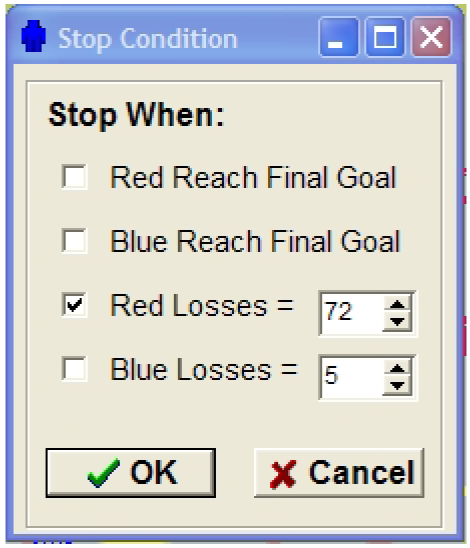


Figure 12. Stopping Conditions

D. MODEL SHORTCOMINGS AND "BUGS"

Over the course of this analysis, the author was challenged to develop "work-arounds" to model the desired behavior which MANA does not do explicitly. Three of the most significant "work-arounds" are discussed in this section. In addition, a brief description of several model "bugs" which were discovered and fixed by the developers as a result of this analysis are presented.

1. Shortcoming in Modeling Jamming

The most significant work around developed was encountered when attempting to model electronic warfare. Critical to examining the effects of electronic warfare was the ability to sever or degrade communication factors during model run time. MANA, in its pure form, only allows the modeler to set communication effects (range, latency, throughput, etc.) at the beginning of each run. Since the purpose of electronic warfare is to reduce or deny the use of portions of the electromagnetic spectrum to an enemy at key times of a battle, the scenario had to have the ability to vary the times at which various communication links were degraded. While electronic warfare encompasses many different aspects, such as negating certain types of fire control systems and sensors, the most common aspect of electronic warfare in ground combat is the jamming of communication links.[27]

27 Puttre, Michael, "International Electronic Countermeasures Handbook," (Horizon House Publications, Inc, Norwood, MA 02062, 2004), pp. 43-56.

Jamming techniques fall into two principle types: deception and noise. Deception jamming is mainly a countermeasure used against search and detection radars. The premise is that signals are generated which are similar to the signals expected by the radar receiver, but of much higher power. Deception jammers receive and "memorize" the victim's transmitted signal and, at an appropriate time, retransmit those signals with suitable amplitude and phase. This causes the generation of false targets, forcing the victim to commit limited assets to fictitious targets. While deception jamming is a valid threat to mainly air forces, the type of jamming modeled in this scenario falls into the second type—noise jamming.

The object of noise jamming is to introduce disruptive signals into hostile electronic equipment so that the wanted signal is obscured. The victim of this disturbance might be a communications network or a datalink, each of which are modeled in this scenario. The effects of this type of jamming range from decreased range of transmission, increased latency, and decreased throughput of the link all the way to complete degradation of the network. From previous discussion of the situational awareness attributes that MANA models, it is clear that MANA is capable of dynamically varying the effects of communication, but it must be done at the beginning of the run.

To accurately model the effects of noise jamming, the author created communication nodes which all Blue forces communicated through. Each agent has the ability to talk through two nodes—a normal communication node (which captures the communication equipment's inherent capabilities while not under jamming) and a degraded communication node (which captures the communication equipment's capability when under jamming). Each of these nodes followed the agents during movement. When the agent desires to communicate with another battlefield agent, it is forced to speak through one of the two nodes. Much like electricity, the agent prefers to send its transmission through the path of least resistance, so that under normal circumstances (no jamming), the agent uses its normal communication node. However, when the communication link is targeted by an enemy jammer, the agent is now forced to use the degraded communication link which has less desirable properties. This work-around, while forcing the creation of many additional agents not represented by any real world counterpart, effectively models the effects of jamming.

2. Dismounting Armored Vehicles

MANA has no pure way to simulate the dismounting of troops from an armored vehicle. Since one of the key attributes of the FCS is its enhanced mobility to deliver combat power to the battle, the ability to simulate delivering dismounts to a place on the battlefield is a must. To accomplish this, the author placed what can best be termed as "phantom" dismounted agents at the dismount point where they remained undetected, unable to shoot, move or sense until their associated infantry carrier arrived at the designated point of the battle.

This behavior could have been modeled many different ways in MANA, each of which are equally plausible. The method used in this analysis was to have all dismounted agents located at the dismount point with the characteristics described above programmed for the RUN START trigger state. Once a friendly agent (ICV) arrived within a certain proximity specified by the modeler, the dismounted agents would revert to the DEFAULT trigger state where all weapons, sensors and other abilities were activated. This provides a very clean way to model the effect of delivering dismounts to the battlefield.

3. Unit Level UAV Activation

The FCS has significant UAV assets, as described in Chapter II. Many of these UAV assets are smaller, vertical take off units that have the ability to be emplaced by an operational unit at the point in the battle which it is most advantageous for that unit to do so. One operational example of this in the given scenario is when the RSV elements are conducting their reconnaissance. Since all UAVs (and other mounted systems for that matter) are bounded by the amount of fuel that they have, they have a limited range or corresponding duration associated with the platform. The RSV would most likely choose to preserve the duration that the UAV would have until it has maneuvered into the reconnaissance area. This would allow for greater unmanned coverage of the battlespace, a desirable characteristic.

To simulate this timely UAV activation, an identical approach was employed as described with the dismounting of armored vehicles. The scenario employs "phantom" UAVs which are activated when their associated controller comes within a certain proximity. This provides yet another clean way to model the effect of saving critical UAV range for surveillance of the objective.

4. "Bugs" in MANA

While every effort has been made by the developers of MANA and the author to ensure that the program was free of computational and logic errors, the model cannot be claimed to be verified or validated. The opening screen of MANA contains the disclaimer that it is a BETA version for scientific and research purposes only. The author's definition for a beta version is a program that is not quite ready to be released, but one which the programmer/author solicits user commentary to uncover programming and logic errors. With the many users of MANA worldwide, over the course of this analysis, the author saw more than 10 different versions of MANA implemented, primarily fixing user discovered bugs. In a recent discussion with the MANA developers, they indicated that they do not believe that the model is completely free of errors, but with user validation for the scenario they are running, the model can provide insights that would otherwise remain undiscovered.

Two such "bugs" were submitted by the author which were critical to the proper running of the scenario at hand. The first bug involved a simple saving problem in which direct fire (Kinetic Energy) weapons would not save the shot radius properly. This affected RPG weapons by diminishing their effect. This bug was readily diagnosed by the developers and a repaired version sent out within a week of the report.

The second bug was a bit more complicated in that the model did not properly model weapons which are organic to armored vehicles. As indicated in Chapter II of this thesis, FCS armor forces—particularly the MCS—have two main weapon systems. One is intended to destroy other armored targets, and the other weapon system is designed to destroy personnel. MANA indicates that it has the ability to do this through the settings on the range tabs when creating agents.

When testing the scenario, the author found that while these settings prevented an armored agent from being killed by a weapon system that was not designed to destroy armor (rifles, artillery, etc.), armored agents were also prevented from destroying "armorless" targets with their close support weapon system. When submitted to the model developers, once again, the problem was diagnosed and a repaired version of the model was sent out in a short order. The ability to communicate directly with the software developers to report possible problems with the model made MANA an easy choice of model when faced with various ABMs.

IV. ANALYSIS METHODOLOGY

The analyst's role is not to provide the answer but…to provide illumination and visibility—to expose some problem in terms that are as simple as possible

Lieutenant General Glen Kent

This chapter explains the analysis methodology, designs and statistical tools used to explore communications and FCS effectiveness in MANA. The objectives are to develop analytic models which describe the output data in order to draw conclusions concerning the effect that communications plays in the effectiveness of the FCS. Any models, therefore, must be able to present findings in a tractable manner. This chapter also devotes some time toward the development of measures of effectiveness—the benchmark that determines levels of success or failure of the FCS. Statistical tools and techniques are also introduced, but left for the reader to explore if further information is desired.

A. METHODOLOGY

Simulations (and Agent-Based Models in particular) are designed to allow decision makers to quickly explore the consequences of tactical decisions. In this case, since the FCS has recently moved into the system design and development stage of acquisition, this may include ensuring that the proper communication characteristics are achieved to ensure mission accomplishment. To do this requires testing a given scenario over many different values of the parameters of interest. Since many models are stochastic (or variable) in nature, replication over a given set of parameter values is required to gain insight into the variability of the outcomes.

The parameters of interest in this analysis morphed from the initial bias and military experience of the author as the analysis progressed. Initially, communication factors including network latency, throughput, reliability, time filtering of messages (ensuring current or valid information is sent), and range were thought to be the only factors of interest. Further thought on the subject revealed that Blue force tactical decisions, such as when to commit to the ground offensive and how to employ unmanned systems, may also have a profound effects on casualties and time of battle.

In addition, it became clear that the enemy also has a hand in the effectiveness of the FCS. A smart enemy may choose to use EW assets, and has the capability to determine the time at which to use those assets. The defensive preparedness (how fortified defensive positions are) of the enemy may have a direct impact on the battle outcome as well. Even with these limited factors, it can be shown that an exhaustive examination of all combinations of these factors, even at a limited number of levels, would result in an untenable experimental design.

To give an example, if only 10 of the factors described above were to be examined at five levels, there are 5^{10} number of runs (almost ten million) required to obtain results on a single experiment at each input combination. To capture the variability of these runs through even modest replication of twenty replications per design point, requires 200 million runs. While agent-based models are designed for quick run time (the scenario implemented in this analysis takes about one minute to run a single replication on a 1.5 GHz Pentium© 4 processor.) Thus, these 200 million runs would take approximately 371 years to complete—of course, by then the analysis would be obsolete. Even this analysis, if completed in a reasonable amount of time with hundreds of processors running, may not sample the "correct" areas of interest.

One of the pioneers in developing methods to examine effects of many factors over many levels is the U.S. Marine Corps Project Albert initiative. Project Albert is the research and development effort of the Marine Corps whose goal is to develop the process and capabilities of Data Farming, a method to address decision-maker's questions that applies high performance computing to modeling in order to examine and understand the landscape of potential simulated outcomes, enhance intuition, find surprises and outliers, and identify potential options.[28]

Data Farming is the method by which potentially millions of data points are explored and captured. It could be considered akin to Data Mining combined with feedback which allows for the more intelligent collection of more data points. This process is made possible, in part, by the exploitation of high performance computing assets and methods. The Project Albert modeling approach is achieved through the

28 Project Albert Description, retrieved 15 May, 2004 from the World Wide Web at http://www.mcwl.quantico.usmc.mil/divisions/albert/index.asp.

development of a suite of models, such as MANA. It is clear that even with high performance computing, a smart experimental design must be used in order to aid the analyst in ensuring a wide sampling of many factors over many levels.

B. EXPERIMENTAL DESIGN

The previous section described one method of exploring factors at various levels known as the full factorial design. Full factorial designs, as indicated, exhaustively look at all combinations of variables at all combinations of levels. These gridded designs are particularly useful for looking at a modest number of factors at a limited amount of levels,[29] however, this method is often infeasible when factors and levels are numerous, due to run-time restrictions. Significant work has been exerted in the development of "smart" designs which sample many values of many factors while maintaining good analytic properties.

One such design is called the Latin Hypercube. Latin Hypercubes, and the Nearly Orthogonal Latin Hypercube (NOLH) designs in particular, are the experimental design of choice in this analysis. Thomas Cioppa, in his PhD dissertation, discusses this branch of experimental designs.[30] His work shows that when the analyst is required to search an intricate simulation model that has a high-dimensional input space characterized by a complex response surface, the NOLH designs are well suited. NOLH designs are characterized by:

- Approximate orthogonality of input factors (uncorrelated inputs)
- Good space filling (i.e. design points are scattered throughout the experimental region with minimal unsampled regions).
- The ability to examine many variables efficiently.
- Flexibility in analyzing and estimating many effects, interactions and thresholds.
- Requires minimal *a priori* assumptions on the response.

[29] Lucas, p. 23.

[30] Cioppa, Lieutenant Colonel Thomas M., *Efficient Nearly Orthogonal and Space-Filling Experimental Designs for High-Dimensional Complex Models*, (PhD. Dissertation, Operations Research Department, Naval Postgraduate School, Monterey, CA), 2002.

A more thorough and technically complete discussion on these experimental designs can be obtained in Cioppa's dissertation.

C. MEASURES OF EFFECTIVENESS

To focus the analysis, two main MOEs were chosen to represent the relative "success" of a combined arms battalion of the Future Force. An MOE represents an objective, quantitative expression of performance appropriate to the context in which it is being used. As indicated by Appleget, two key measures used in the FCS AoA included the time to accomplish the mission and the number of Blue losses. [31]

The time to accomplish the mission represents the speed at which the Blue force exacts a certain amount of attrition on the enemy. All experiments in this analysis examined this time as a factor of the point (in terms of their own casualties) at which the Red forces broke contact. Of course, the point at which the Red force makes this determination is variable in its own right, so each experiment was conducted at two nominal values of a determined enemy—when they receive 50 percent and 75 percent casualties. These values assume a very determined and disciplined enemy that understands the criticality of their mission.

The number of Blue losses indicates a shift in the post Vietnam War measure of tracking enemy "body counts" to the number of U.S. servicemen losses. A casual look at what is reported on U.S. news networks reveals a near non-existent reporting of enemy casualties, however, the loss of a single U.S. serviceman to enemy fire is front page news. Any tactical or equipment procurement decision must take into account the risk to U.S. servicemen. Both of these measures are readily available in MANA.

D. EXPERIMENTAL SETS

Three experimental sets are examined in this analysis. They are presented in detail below.

1. Experimental Set 1—No EW Case

The first experimental set sought to examine the first two analysis questions, which are:

[31] Appleget, p. 15.

- What characteristics of communications are imperative and at what levels are they significant for a combined arms battalion of the Army's Future Force employed in the attack?
- How do network latency, range, reliability and throughput affect the Future Force's ability to fight and win decisively?

This experimental set can be considered the baseline case that examines how variations in the communication factors affect the performance of the Blue forces. These runs assume that the enemy does not possess EW or chooses not to use this capability. In keeping with the spirit of agent-based models, this analysis begins by examining a large number of variables and distilling these variables as analysis indicates significance to the overall problem. The final variables are selected based on these many pre-production runs focusing the analysis. The final MANA simulation was run exploring seven communication factors and two tactical decision factors at two designated enemy breakpoints. The levels were chosen by using military experience and judgement from many small interactive experiments. The ten variables and the ranges examined are presented below with the corresponding MANA variable in parenthesis. A summary of these values (in terms of MANA converted values) is shown in Table 5.

- Latency—(Latency) from a delay a few seconds to a few minutes.
- Range—(Range) from the ability to communicate over the entire battlespace to a diminished range of 50 percent of the battlespace.
- Reliability—(Reliability) from 100 percent reliable to a network that was only 50 percent reliable.
- Throughput—(Capacity) from a nearly infinite capacity (bandwidth) to a capacity which made electronic communications nearly non-existent.
- Filtering mechanism—(Max Information Age) from allowing only the most current information to allowing even very stale information to pass through the network.

- Buffer Size—(Queue Buffer Size) representing the hardware's ability to store messages until they can be sent, ranging from a very large buffer to a very small buffer.

- Method of Transmission—(Guaranteed Delivery or Fire and Forget) representing the option to send the message once or send until received.

- Early UAV Employment—(UAV Ideal Enemy / Run Start Trigger State) establishes the priority of UAV effort early in the battle to one of four categories: dismounted infantry, air defense assets, mortars, or armor.

- Late UAV Employment—(UAV Ideal Enemy / Default Trigger State) establishes the priority of UAV effort late in the battle to one of the same four categories discussed above.

- Enemy Breakpoint—(Red Stopping Condition) evaluated at 50 percent and 75 percent casualties.

Factor	Lower Value	Upper Value
Latency	0	20
Range	500	1000
Reliability	50	100
Capacity	1	50
Max Info Age	1	50
Queue Buffer Size	0	200
GD or F&F	Yes	No
Early UAV Effort	1	4
Late UAV Effort	1	4
Enemy Breakpoint	48	72

Table 5. Factor and Level Summary for Experiment 1.

Using a NOLH design with nine factors evaluated at both enemy breakpoints (132 design points) and 35 replications per design point, time of battle and Blue force casualties are examined. The desire is to provide insight on which communications factors are significant to the Blue forces against an enemy who does not use EW.

2. Experimental Set 2—Enemy EW Case

The second experimental set seeks to examine the third analysis question, which is:

- How do network attacks (complete and partial degradation) and the Future Force's ability to respond to the attacks hamper fighting ability?

This experiment expands on the first, however this experiment assumes that the enemy force both possesses EW and chooses to use that capability. To represent the decisions that the enemy has, the time and duration at which the enemy uses EW is examined. The time that EW is employed can have a profound effect based on the communications reliance of Blue weapon systems at a particular point in the battle. The duration of EW takes into account the fact that the U.S. military has redundant means of communication, but any shift in means of communications will require time to implement.

The second experimental set was run exploring the ten factors described in the first experiment along with two additional factors i.e. the time of EW and duration of EW. The levels were chosen to account for enemy employment of EW through all phases of the Blue force attack and the spectrum of Blue response to that EW. The two additional variables and the ranges examined are presented below with the corresponding MANA variables in parenthesis. A summary of these values (in terms of MANA converted values) is shown in Table 6.

- Time of EW—(Jammer Duration Run Start Trigger State) from battle commencement to well into the dismounted ground offensive.
- Duration of EW—(Jammer Duration Spare 1 Trigger State) from near immediate response to total loss of communications from initiation of EW on.

Factor	Lower Value	Upper Value
Latency	0	20
Range	500	1000
Reliability	50	100
Capacity	1	50
Max Info Age	1	50
Queue Buffer Size	0	200
GD or F&F	Yes	No
Early UAV Effort	1	4
Late UAV Effort	1	4
Duration of EW	100	600
Time of EW	10	500
Enemy Breakpoint	48	72

Table 6. Factor and Level Summary for Experiment 2.

Using a NOLH design with eleven factors evaluated at both enemy breakpoints (132 design points) and 35 replications per design point, time of battle and Blue force casualties are examined. The goal is to provide insight on which communications factors are significant to the Blue forces and how the enemy interdiction of the communications hampers mission accomplishment.

3. Experimental Set 3—Most Critical Communication Link

The final experimental set seeks to examine the fourth analysis question, which was:

- If destroyed or hampered, which communication link(s) most affect the Future Force in terms of mission accomplishment?

This experimental set changes the focus from conducting operations in a degraded communications environment to conducting operations in an environment where complete degredation is experienced in a particular battlefield operating system. To examine this, additional MANA agents are created to achieve the effect of completely severing a particular communication link. Blue forces are aggregated into three main categories: UAVs, armor assets, and dismounted forces. Enemy jammers then target only specific communication links of these categories. The activation times of each jammer are then varied to examine the effectiveness of the Blue forces.

As described in experimental set two, to represent the decisions that the enemy has, the time at which the enemy used EW to sever a particular communication link is examined. The final experimental set is run exploring three factors of the time of EW for each of the three categories. The levels are chosen to account for enemy employment of EW through all phases of the Blue force attack. Once a communication link is severed, it is assumed unrecoverable to Blue forces. The variables and the ranges examined are presented below with the corresponding MANA variables in parenthesis.

- Time of EW—(Jammer Duration Run Start Trigger State) from battle commencement to well into the dismounted ground offensive. This is implemented for the UAV, armor and dismounted jammers.

Factor	Lower Value	Upper Value
Time of Dismounted EW	1	800
Time of Armor EW	1	800
Time of UAV EW	1	800
Enemy Breakpoint	48	72

Table 7. Factor and Level Summary for Experiment 3.

Using three stacked orthogonal Latin hypercube designs with three factors evaluated at both enemy breakpoints (102 design points) and 35 replications per design point, time of battle and Blue force casualties are examined. The goal is to provide insight on which communications link is most significant to the Blue forces.

E. STATISTICAL TOOLS AND TECHNIQUES

At this point, the model has been described, MOEs defined, factors determined at their appropriate levels, and the experimental designs fixed. Once these items have been combined to yield the output of the model, the analyst must determine methods to evaluate the results. This section outlines the methods and procedures used in this analysis to draw conclusions from the data.

While there are many analysis techniques that could have been applied to the output datasets, this analysis concentrates primarily on four main techniques: graphical analysis, multiple regression, regression trees and classification trees. All of these techniques can be considered complimentary in nature, each yielding insights about the data in their own right.

1. Graphical Analysis

Graphical analysis is probably the least technical of all analysis methods, requiring no assumptions about the data. It involves simply plotting aspects of the data to uncover insights on the behavior. It has been said that "a picture is worth a thousand words" and this is certainly true in this application. Graphics can provide insights interpretable by audiences without an analysis background, particularly useful in the military environment when conveying results to a tactical commander.

2. Multiple Regression

Multiple regression is the standard technique for assessing how various predictors (inputs) relate to a response. One subset of multiple regression is linear regression which is used to describe the effect of continuous or categorical variables upon a continuous response. The linear regression model assumes that the response is obtained by taking specific linear combinations of the coefficients of the predictors and adding random variation (error). The error is assumed to have a Gaussian (normal) distribution with constant variance and independent of the predictor values.[32] Regression is useful for determining which predictor variables have an effect on the output, and is the primary means to determine which communication factors are significant to the FCS.

3. Regression and Classification Trees

The basic principal of tree models is to partition (in a recursive manner) the space spanned by the input variables to maximize a score of class "purity."[33] Purity, roughly speaking, means that the majority of points in each cell of a partition belong to a similar class. Each partition may have additional splits to increase the purity of the previous split, thus giving the analyst an idea of the importance of the factors. Factors which increase the purity most are "most" important and subsequent splits are "less" important. In addition, this can give indication to the levels at which the factors are important. Tree models have fewer requirements on the underlying assumptions concerning the output

[32] Hand, David, Heikki Mannila and Padhraic Smyth, *Principles of Data Mining*, (The MIT press, Cambridge, Massachusetts, 2001), p. 367-289.

[33] Hand, p. 343.

data and for this reason are often very useful analytic tools for exploring the relationships in the output data. Trees can highlight where the relationships of significant factors occurred.[34]

The basic difference between regression and classification trees is that a regression tree yields a continuous output while classification trees predict a categorical output. In this analysis, a regression tree was used to yield a prediction on the time of battle or number of Blue casualties, based on partitions, and was used primarily to confirm the most important factors discovered using multiple regression. In this analysis, classification trees are used to predict whether the battle takes a "short," "medium," or "long" period of time or if casualties are "low," "medium," or "high." This gives insights on the level that a specific factor becomes important to yielding a short battle or minimal casualties.

F. SOFTWARE USED IN THIS STUDY

To attempt to conduct any parametric analysis of any sort would be a near impossible task without the aid of statistical software. This section briefly discusses the packages used to arrive at conclusions drawn from the data.

1. JMP Statistical Discovery Software™

JMP was chosen as the platform to conduct a majority of the data analysis. JMP is a product of the SAS Institute® and is advertised as a software package for interactive statistical graphics.[35] JMP includes:

- A spreadsheet for viewing, editing, entering and manipulating data.
- A broad range of built in statistical and model building menus to simplify analysis.
- Extensive graphics capability to quickly generate the most commonly used statistical inference graphics.
- Simple and intuitive point-and-click interface.
- Extensive help library to assist with interpretation of analysis products.

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[34] Brown, *Objective Force Urban Operations Agent Based Simulation Experiment*, p. 15.

[35] *JMP Introductory Guide, Version 5*, (SAS Institute Inc.,Cary NC. 2002) p. 1.

While JMP is limited in some respects when performing non-standard analysis (to which other packages are more robust), it provides sufficient capability to examine the data with the techniques desired for this analysis.

2. Clementine®

Clementine is a data mining application. Data mining offers a strategic approach to finding useful relationships in moderate to large data sets. In contrast to more traditional statistical methods, the user does not necessarily need to know what they are looking for when starting the analysis. Data can be explored, fitting different models and investigating different relationships until useful information is found.[36] The Clementine interface makes data exploration relatively easy. The interface allows the user to drag various nodes onto the operating palette to manipulate the data. Nodes are connected together to form streams which, when executed, let the user visualize relationships and draw conclusions. In this thesis, classification and regression trees are created using Clementine to confirm results from JMP.

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[36] Clementine Product Description, Clementine Data Mining System Version 8.0, (SPSS Inc., 2000) retrieved on May 13, 2004 from the world wide web at http://www.spss.com/clementine.

V. DATA AND DATA ANALYSIS

This chapter outlines the significant findings and methods used to arrive at conclusions. It is presented in three sections: data collected, pre-production observations and thesis question-based observations. The section on data collected outlines how pertinent items were extracted from the raw data used for future data analysis. Pre-production observations present some of the "intuitive" findings of the analysis and show why certain factors were omitted in production run simulations. The thesis question-based observations present analysis which drove the conclusions presented in Chapter VI. This section is ordered in the same manner as the research questions were posed.

A. DATA COLLECTION AND CLEANING

For each experimental set, the simulation output data consists of many observations and several measures of effectiveness. Many of these measures are not useful for the analysis at hand (such as squad by squad breakdown of casualties). Prior to any analysis, the data set must be pared down to contain only the input factors to be examined and the desired measures of effectiveness.

As previously discussed, MANA is a stochastic simulation which, by nature, yields a distribution of outcomes for a set of input parameters. This variability can be very large in some circumstances. Fitting a model with highly variable data often leads to poorly fit models which may be scrutinized by those in the field of data analysis when drawing conclusions. In an attempt to create better fitting models without losing the core information, replication between design points is aggregated into a single measure of centrality.

Two main measures are often used: the average and the median of the outcomes. The median is a method that is useful when significant outliers exist. This non-parametric measure simply rank orders all observations and selects the observation that lies in the middle. Another measure is the average. The average is the measure used in this analysis. While it can be shown that in most cases in this analysis, both measures are the nearly the same, the average is a term that is widely known and appeals to the knowledge base of those who may not have an extensive statistics background. Using the average in this type of analysis yields (somewhat artificially) a higher R^2 value, but also allows the analyst to pick up factors which otherwise might have been missed if aggregation is not used.

To effectively use the average as a measure of centrality, it must first be shown that significant outliers do not exist for outcomes and second to show that a majority of the outcomes lie around that average value. Both of these characteristics are demonstrated by a histogram of output values and its corresponding QQ plot.[37] Ideally, one hopes to see a distribution of outcomes that resemble the Gaussian or Normal distribution. Selecting any design point (combination of input factors) from the data set and plotting the outcomes of that design point in a histogram roughly demonstrates this relationship. One such design point is shown in Figure 13 below. The reader notes the bell-shaped curve which resembles a Normal Distribution. Its corresponding QQ plot graphically confirms this assumption.

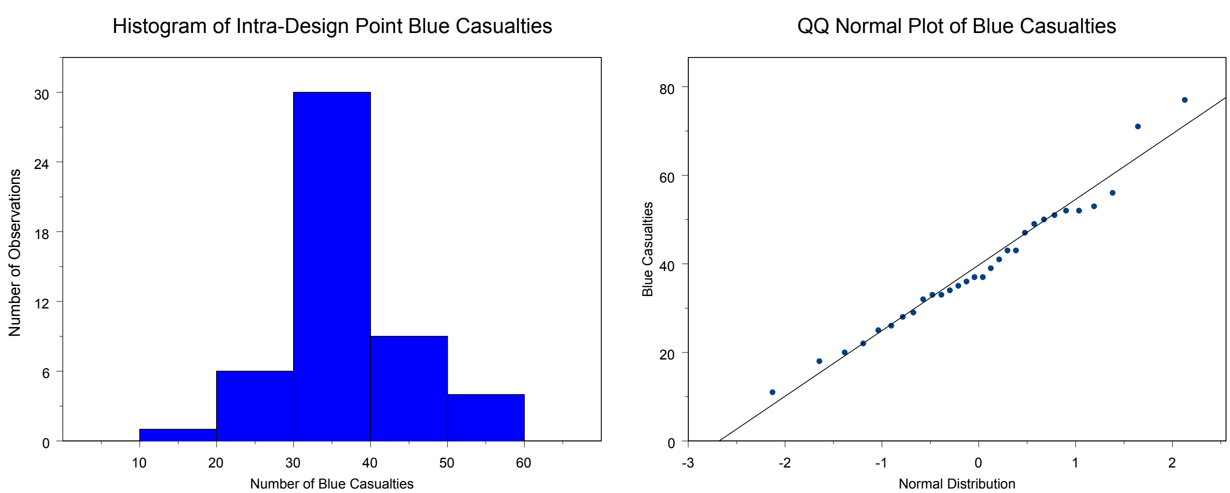

Figure 13. Histogram and Corresponding QQ Plot of One Design Point

To analytically confirm intuition about the graphical observation of normality, the Shapiro-Wilk test for normality may be conducted.[38] These results are posed in a hypothesis test setting, where the null hypothesis is that the distribution comes from a

[37] Hamilton, Lawrence C. *Regression With Graphics, A Second Course in Applied Statistics*, (Duxbury Press, Belmont, CA 94002, 1992), p. 13-15.

[38] Conover, W.J. Practical Nonparametric Statistics, Third Edition, (John Wiley & Sons, Inc. New York, 1999), p. 450.

normal distribution. Conducting this test yields a p-value of 0.65, indicating strong evidence that the null hypothesis of the data's normality should not be rejected. These results are typical for most input combinations examined.

B. PRE-PRODUCTION RUN OBSERVATIONS

Analysis is often an iterative process that is adjusted to examine the questions of interest. This is certainly the case in this analysis. Initially, the author thought that including every possible factor that might have an effect on the FCS effectiveness would be the "best" way to tackle the problem at hand. It became evident early on, however, that in order to examine the communication questions posed, the factors examined must be pared down as insights are uncovered. Several factors such as the time at which the Blue forces commit to the dismounted ground offensive, enemy fortification and a large range of enemy breakpoints are removed from production runs to uncover communication insights. The main reason for omission is that these factors tend to overwhelm the importance of communication factors examined and make them less significant.

"Infantry must move forward to close with the enemy."

General George S. Patton

1. Committing to the Dismounted Offensive

In this pre-production experimental set, the time at which the Blue forces commit to the dismounted offensive is varied from very early in the battle to very late in the battle. Other communication factors are also varied with the goal of uncovering the significance of communications factors. This "drowning out" of the communication factors can be seen by examining a multiple regression model that shows the relative importance of factors. The model takes into account all main effects (no interactions) and shows that even with a well-fit model (adjusted R^2 of 0.88), the effect of committing to the ground offensive (Time of Phase II) is nearly an order of magnitude larger in importance than its nearest communication factor: communication range (CommRange).

This relative importance of the factors manifests itself in the Sum of Squares (SoS) computation shown in Figure 14. The sum of squares indicates the amount of variability that the factor of interest accounts for. A large value indicates significance to the fit of the model. Since the objective of this analysis is to determine the importance of communication factors, the time to commit to the dismounted offensive is omitted from future experimental sets with the intent of amplifying communication effects in future analysis. This however brings an important tactical insight to light, namely, that even with modern technology, leadership decisions critically affect battles. Additionally, the insight of allowing the NLOS to exact as much attrition as possible prior to committing dismounted forces is noted and examined in further detail.

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
CommRange	1	1	10512.994	25.0362	<.0001
CommLink MaxAge	1	1	2051.053	4.8845	0.0378
CommLink BufferSize	1	1	4723.574	11.2490	0.0029
Time of Phase II	1	1	83359.720	198.5171	<.0001
Latency	1	1	413.812	0.9855	0.3316
Reliability	1	1	1.160	0.0028	0.9586
Capacity	1	1	126.700	0.3017	0.5883
CommSettings Guaranteed	1	1	729.129	1.7364	0.2012
Early UAV Effort	1	1	606.032	1.4432	0.2424
Late UAV Effort	1	1	829.123	1.9745	0.1739

Figure 14. Tests of Main Effects (Linear Regression Model Fit)

Many pre-production runs show that if the Blue forces commit to the dismounted offensive late in the battle, they receive fewer casualties; however, the time of battle is much longer. This leads to the question, why commit to the dismounted ground offensive at all? Observing the simulation during run time reveals that if the NLOS systems are given longer to attrite the enemy forces, they are, in effect, "softened" up and offer less resistance to the dismounts, thereby decreasing the overall Blue casualties. While a tactical commander might be tempted to continue the NLOS offensive for long periods, often times, commanders are bound by time and logistic constraints to ensure coordination with other units.

The reader may recall that the Blue forces had the mission of destroying enemy in their area of operations in order to facilitate follow-on movement and operations in theater. If the unit is not able to destroy enemy air defenses prior to air insertion of follow-on forces, a single enemy air defense missile might completely destroy an incoming troop carrying aircraft, significantly increasing Blue casualties. Time to complete a battle is a significant military factor that cannot be ignored.

To examine the tactical question of the "correct" duration of the NLOS fight, several smaller runs were executed to determine the effectiveness of the NLOS systems. Essentially, these mini-experiments look at the Red casualty results if only reconnaissance assets (UAVs and RSVs) are committed to locate the enemy and feed this information to the NLOS to "win" the battle. What we see is that there is a point of diminishing returns on the NLOS. After a certain period of time, the NLOS are unable to finish the enemy. These results are summarized below in Figure 15.

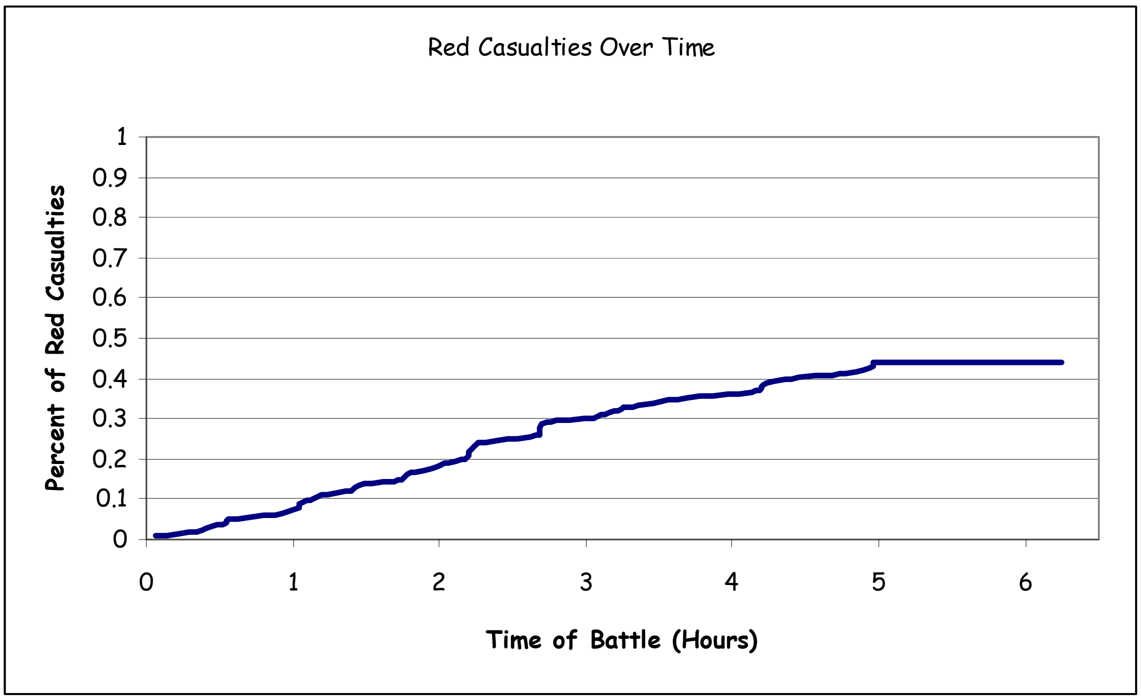

Figure 15. NLOS and Reconnaissance Assets Only (Enemy Attrition Over Time)

Figure 15 indicates that if NLOS are the only "killer" team employed, they would not exact even 50 percent attrition on the enemy after six hours of continuous fighting. In short, NLOS cannot win the battle alone. It should also be noted that in this configuration, the Blue forces suffered only one casualty, a UAV which was shot down by enemy fire.

As a comparison, when committing to the dismounted ground offensive after the NLOS have exacted *some* attrition, the following results are noted. While Blue forces receive casualties at a much higher rate than the NLOS fight alone, the rate at which Blue forces attrite the Red forces is also much higher. Figure 16 (best when viewed in color) shows an example of this.

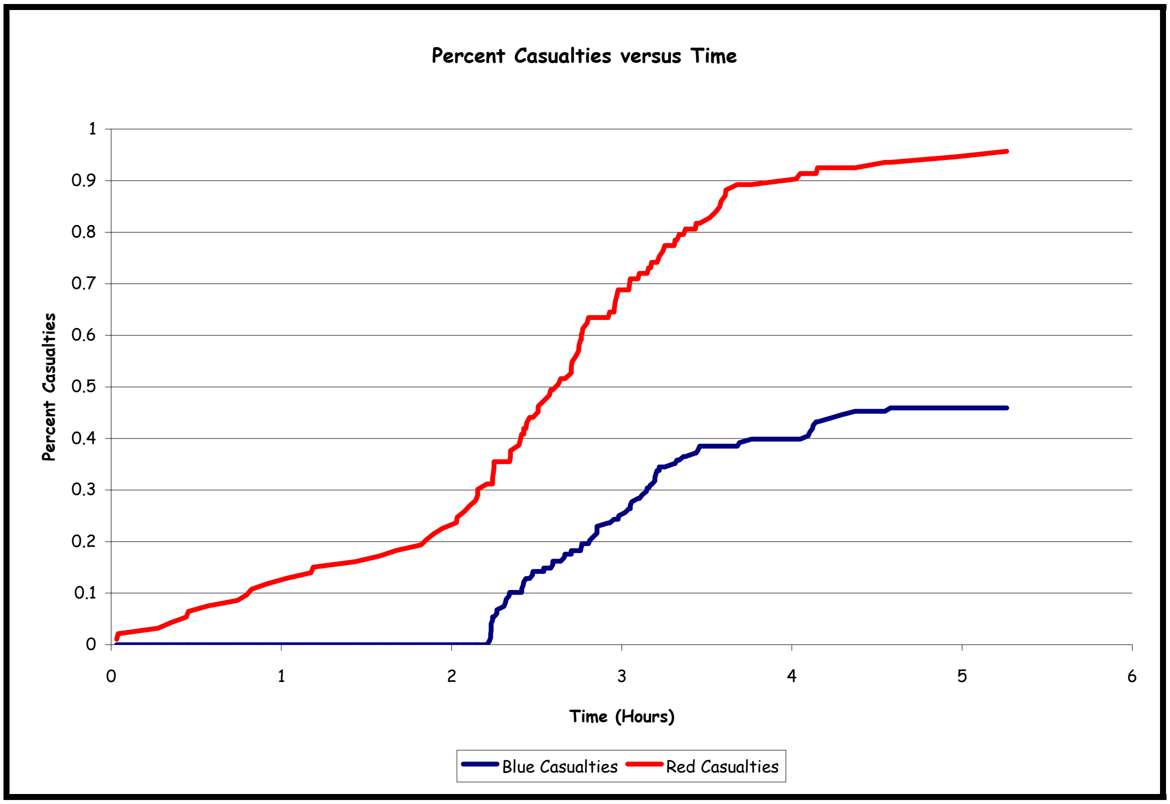

Figure 16. All FCS Assets (Enemy and Friendly Attrition Over Time)

The old adage of "nothing ventured, nothing gained" comes to mind when viewing Figure 16. This figure indicates that when Blue dismounts are committed to the battle (around two hours into the battle), the rate at which Blue takes casualties increases significantly, however, so does the rate of Red casualties. This shows that a finishing force must be committed by the Blue forces to ensure a decisive victory.

2. Enemy Fortification Effects

As one might expect, an enemy who is well prepared and dug in is a much more difficult enemy to fight. In MANA, the fortification level of the enemy is quite easily modeled by increasing or decreasing weapons effectiveness of Blue systems on that enemy. Much like the example provided above, including enemy defensive preparation in the analysis tends to "drown out" any significance of communications in the battle.

In this experiment, the enemy fortification levels are varied from a hasty defense, where very little protection is offered to the enemy, to scenarios where the enemy is well dug in and obscured from Blue detection. Results indicate that if the enemy is well prepared and fortified, Blue casualties are substantially higher than that of an enemy who is only hastily prepared. In addition, battles tend to be longer for a well prepared enemy.

To demonstrate the "drowning out" of the communication factors, multiple regression is again used to show the relative importance of factors. The model takes into account all main effects (no interactions) and shows that even with a well-fit model (adjusted R^2 of 0.98), the effect of enemy fortification (Enemy Fortification) is nearly three orders of magnitude larger in importance than its nearest communication factor: communication range (CommRange). The SoS results are shown in Figure 17. Once again, since the objective of this analysis is to determine the importance of communication factors, the level at which the enemy is prepared is omitted from future analysis with the intent of amplifying communication effects in future analysis.

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F	
Duration of EW	1	1	37.6649	4.9696	0.0350	
Time of EW	1	1	401.7391	53.0066	<.0001	
Enemy Fortification	1	1	9838.7107	1298.149	<.0001	
Latency	1	0	0.0000	.	.	LostDFs
CommRange	1	1	11.1096	1.4658	0.2373	
Early UAV Effort	1	1	0.3591	0.0474	0.8294	
Late UAV Effort	1	1	2.4067	0.3175	0.5781	
Reliability	1	0	0.0000	.	.	LostDFs

Figure 17. Tests of Main Effects (Linear Regression Model Fit)

Figure 17 indicates that a model which includes only the factor of Enemy Fortification almost exclusively describes the outcome of a battle. It is worth noting that, in this scenario, communication factors are a second order effect.

3. Enemy Breakpoint Effects

As has been shown in the previous two examples, non-communication related effects can have a significant effect on a battle outcome. While important in their own rite to a battlefield commander, when examining the communications questions at hand, care must be taken to ensure that the desired factors are analyzed. Another factor examined is enemy breakpoint. Early experiments show that, much like the previous two examples, when enemy breakpoint is varied over a wide range of values, this factor tends to dissolve the importance of communications in the battle.

In this experiment, the enemy breakpoint is varied from 30 percent to 75 percent. This represents the determination of the enemy to hold the ground that they were directed to. Results show that if the enemy breaks contact early in the battle, Blue casualties tend to be much lower than when the enemy fights longer. In addition, when the enemy fights longer, the battles tend to be longer.

A multiple regression model is created to assess the relative importance of factors. The model takes into account all main effects (no interactions) and shows that even with a well-fit model, (adjusted R^2 of 0.91) the effect of enemy breakpoint (Enemy Breakpoint) is nearly three orders of magnitude larger in importance than its nearest communication factor: queue buffer size (Queue Buffer Size). The SoS results are shown in Figure 18. Since the objective of this analysis is to determine the importance of communication factors, the level at which the enemy breaks contact is only evaluated at two representative values in the final experiments.

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
Latency	1	1	6.26	0.0036	0.9523
Range	1	1	275.84	0.1590	0.6916
Capacity	1	1	193.27	0.1114	0.7398
Max Info Age	1	1	1121.29	0.6462	0.4249
Queue Buffer Size	1	1	1317.42	0.7592	0.3873
Time of Phase II	1	1	414311.32	238.7578	<.0001
Duration of EW	1	1	1247.62	0.7190	0.4001
Time of EW	1	1	0.23	0.0001	0.9909
Red Breakpoint	1	1	709634.04	408.9453	<.0001

Figure 18. Tests of Main Effects (Linear Regression Model Fit)

Figure 18 indicates that a model which includes a factor of Red Breakpoint diminishes any communication significance.

4. Summary of Pre-Production Observations

Despite the overwhelming of communications importance, each of the pre-production experimental sets uncover important tactical insights important to a tactical commander. The first set indicates that the increased lethality of the FCS NLOS assets provides a capability that must be allowed to attrite the enemy as long as possible. This, however, must be balanced with time constraints. In addition, it must be noted that even with this increased lethality, NLOS alone cannot win the battle. The second set shows that an enemy that is well fortified requires more effort to destroy. The final set shows the importance of non-traditional military assets such as psychological operations in diminishing the enemy's will to fight. An enemy who loses his will to fight early in the battle will result in a less bloody battle that will cease hostilities much quicker. To summarize, leadership, enemy defensive posture, and the enemy's will to fight are more important than any marginal technical factors.

C. THESIS QUESTION BASED ANALYSIS

Armed with pre-production analysis observations, experimental sets as detailed in Chapter IV were conducted. Each of the data sets are analyzed using both MOEs and various methods to determine the significance of communications effects on the battle outcome. The following observations are presented.

1. Communication Characteristics and Levels of Significance Analysis

The heart of the analysis lies in developing insights into how systems should be designed to ensure a capable FCS force. The first two analysis questions that we are seeking to uncover insights for are:

- What characteristics of communications are imperative and at what levels are they significant for a combined arms battalion of the Army's Future Force employed in the attack?
- How do network latency, range, reliability, and throughput affect the Future Force's ability to fight and win decisively?

The first experimental set was used to examine these questions. Recall that this experimental set varies seven communication factors and two tactical employment factors (UAV employment focus) at two representative enemy breakpoints under conditions of no EW. Conducting multiple regression on all main effects, two term interactions and quadratic effects using Blue casualties as the response yields the following model shown in Figure 19 (best when viewed in color).

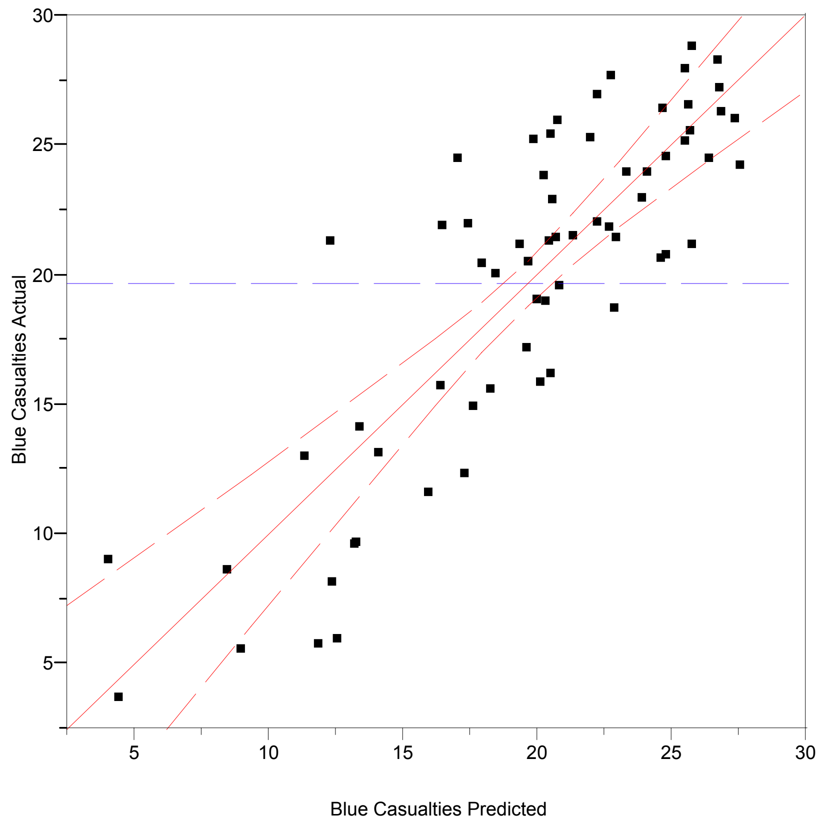

Figure 19. No EW Regression Model (50% Enemy Breakpoint / Blue Casualty MOE)

Figure 19 shows the fitted model based on the regression analysis. Ideally, the data points would fall along the Red centerline or the line of fit. The distance from each point to the line of fit is the error or residual for that point. The adjusted R^2 for this model, indicating how well the model fits the data, is 0.73, indicating a fairly good fit for this type of model. The significant factors and interactions that have the largest effect in this regression analysis are shown in Table 8.

Factor	Sum of Squares
Range	1145.02
Latency	311.04
Latency / Range Interaction	251.82
Capacity	141.84
Reliability	113.16

Table 8. Significant Factors (No EW 50% Enemy Breakpoint / Blue Casualty MOE)

Conducting similar analysis on this data set, using the time of battle as the response once again leads to a fairly well-fit model (adjusted R^2 of 0.73). The significant factors and interactions that have the largest effect in this regression analysis are shown in Table 9.

Factor	Sum of Squares
Range	29224.69
Latency	7946.17
Capacity	3529.47
Reliability	3518.87
Range / Capacity Interaction	3095.31
Latency / Range Interaction	2491.45

Table 9. Significant Factors (No EW 50% Enemy Breakpoint / Time of Battle MOE)

Prior to drawing any conclusions about the results of the regression analysis, it makes sense to compare the results when the enemy breakpoint is set at 75 percent. Conducting a linear regression on all main effects, two term interactions and quadratic effects when evaluated at 75 percent enemy breakpoint and using Blue casualties as the MOE yields a fairly well-fit model (adjusted R^2 of 0.68). The significant factors and interactions that have the largest effect in this regression analysis are shown in Table 10.

Factor	Sum of Squares
Range	1548.37
Latency	536.05
Capacity	346.89
Latency / Range Interaction	236.41
Range / Capacity Interaction	178.51
Reliability	137.51

Table 10. Significant Factors (No EW 75% Enemy Breakpoint / Blue Casualty MOE)

Conducting similar analysis on this data set, using the time of battle as the response once again leads to a fairly well-fit model (adjusted R^2 of 0.63). The significant factors and interactions that have the largest effect in this regression analysis are shown in Table 11.

Factor	Sum of Squares
Range	68290.62
Latency	34513.02
Capacity	28891.66
Latency / Range Interaction	21329.51
Reliability	12574.40
Reliability / Capacity Interaction	10511.16

Table 11. Significant Factors (No EW 75% Enemy Breakpoint / Time of Battle MOE)

Aggregating these results into a single table which shows the prominence of factors examined in these data sets, helps to detect recurring patterns in the analyses. Table 12 records the number of times a specific factor appeared in the four regression analyses.

Factor	Number of Times Deemed Significant
Range	4
Latency	4
Capacity	4
Reliability	4
Latency / Range Interaction	4
Range / Capacity Interaction	2
Reliability / Capacity Interaction	1

Table 12. Aggregation of Significant Factors (No EW / All MOEs & Enemy Breakpoints)

The overlap of significant factors gives insight concerning the importance of the factors. The fact that range, latency, capacity, reliability and the interaction between latency and range occurred in all data sets using both MOEs is noteworthy. This suggests that these factors could be the prominent communication factors which have an effect on the effectiveness of the FCS. Further intuition suggests that since range and latency are the "top two" factors in all four models, suggests that we can refine this finding further to say that range and latency are the "most" important communication factors in this scenario.

Observing leverage plots of range and latency uncovers insights as to the relationship of these factors.[39] Figure 20 (best when viewed in color) indicates that as

[39] *JMP Statistics and Graphics Guide, Version 5*, (SAS Institute Inc.,Cary NC. 2002) p. 193.

range is increased (representing an increased ability to communicate over the entire battlespace) and as latency is decreased (representing the characteristic of an efficient network) one could expect that the time of battle (and Blue casualties) are decreased. This would serve to confirm one’s intuition that adding increased communications capability is beneficial.

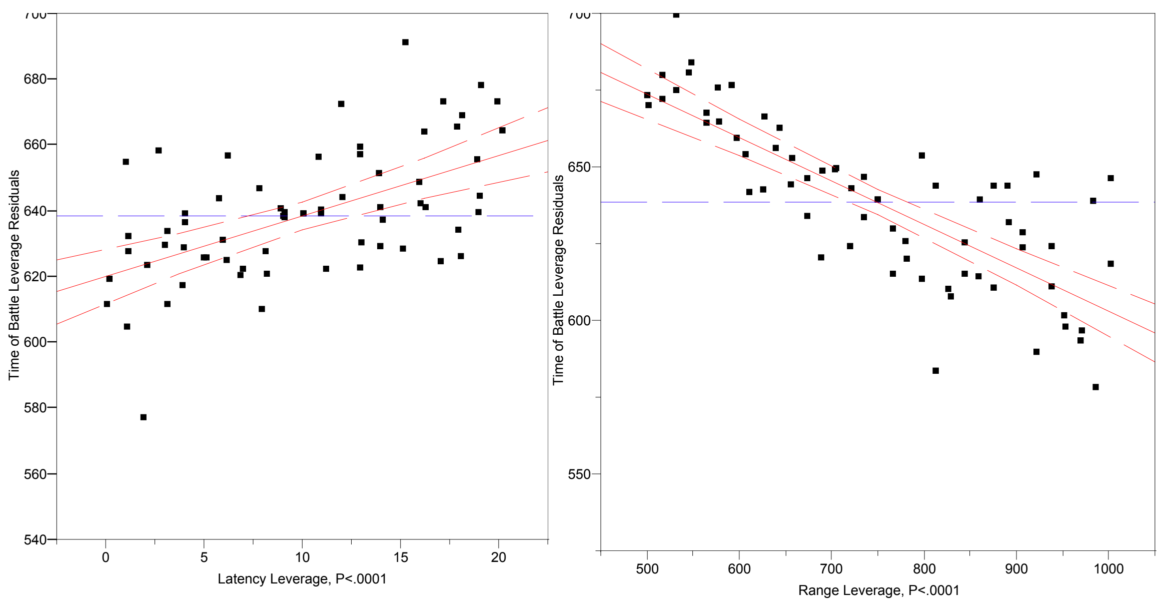

Figure 20. Leverage Plots of Range and Latency Effects

Noting that there is a prominent interaction as well in the “top” communication effects warrants further examination. The interaction between range and latency can best be described through an interaction plot.[40] The interaction plot graphically portrays the relationship between the two factors. As shown in Figure 21, when latency is high, (representing slow communications) range does not play a significant role in determining the battle outcome. However, when the network is very responsive, (low latency) the ability to communicate over the entire battlespace is very significant. In other words, if the network is too slow to respond to current intelligence concerning the enemy, the range of communications doesn’t matter. (By the time the intelligence is received by the “killer” team, the enemy has relocated and any fires brought upon that enemy are exhausted in vain.)

[40] *JMP Statistics and Graphics Guide*, p. 244.

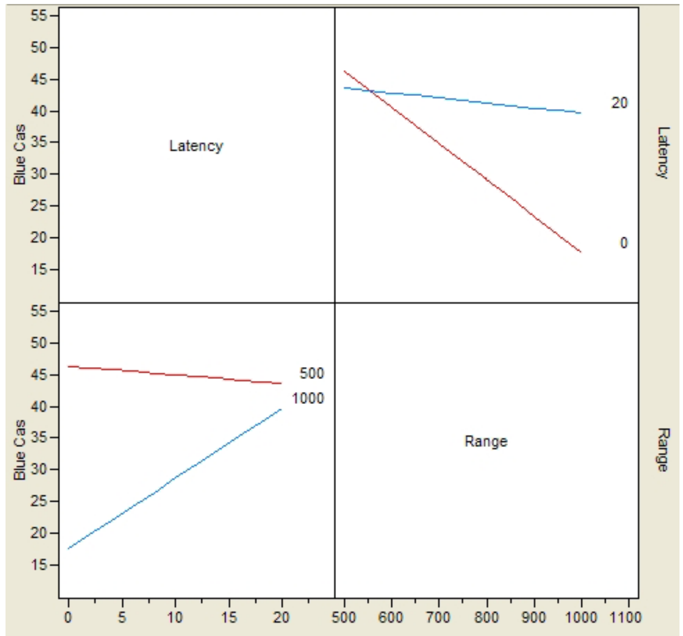

Figure 21. Interaction Plots of Range and Latency

Feeling confident that these data sets have uncovered insights as to the significance of communications factors, further analysis is required to examine the levels at which these factors are important. To examine this question, regression and classification trees are constructed on the non-aggregated data. Guided by the regression analysis, a few key points can be taken away from the regression tree shown in Figure 22.

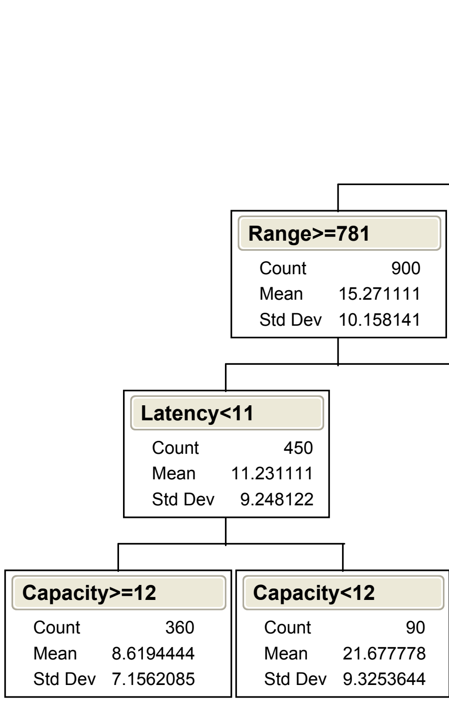

Figure 22. Regression Tree (No EW, 50% Enemy Breakpoint / Blue Casualty MOE)

A quick look at this regression tree indicates that there are 1980 total observations, as shown in the top node or "root" of the tree. Additionally, the average number of Blue casualties is indicated to be about 20. The first split to increase purity of this model occurs when range is at 781. This split indicates two main things. Firstly, it indicates that the most important factor in determining the number of Blue casualties is communications range. Secondly, that when range is at least 781, the average number of Blue casualties is about 15. This process of increasing purity continues down to the terminal nodes where additional insights may be discovered.

Applying this explanation of regression trees, the first conclusion that may be extracted is that when the communication range is greater than 781 (the ability to communicate over 78 percent of the battlespace) generally good things happen for the Blue forces. Note the left side of the regression tree predominantly yields lower mean Blue casualties than when range is less than 781. Secondly, when latency is less than 11 (meaning that communications are received by the sender within one minute of sending), generally casualties are lower for the Blue forces. Finally, a great disparity exists when looking at the relative capacity of the network. While there is no direct relationship between the capacity parameter in MANA and bandwidth, this factor suggests that there is a region where the throughput of the network matters and should be examined in greater detail using a physics-based model where specific bandwidth requirements are modeled.

A comparative analysis using a classification tree where Blue casualties are segregated into three quantiles (lower, middle and upper—representing low, medium and high casualties) shows similar results.

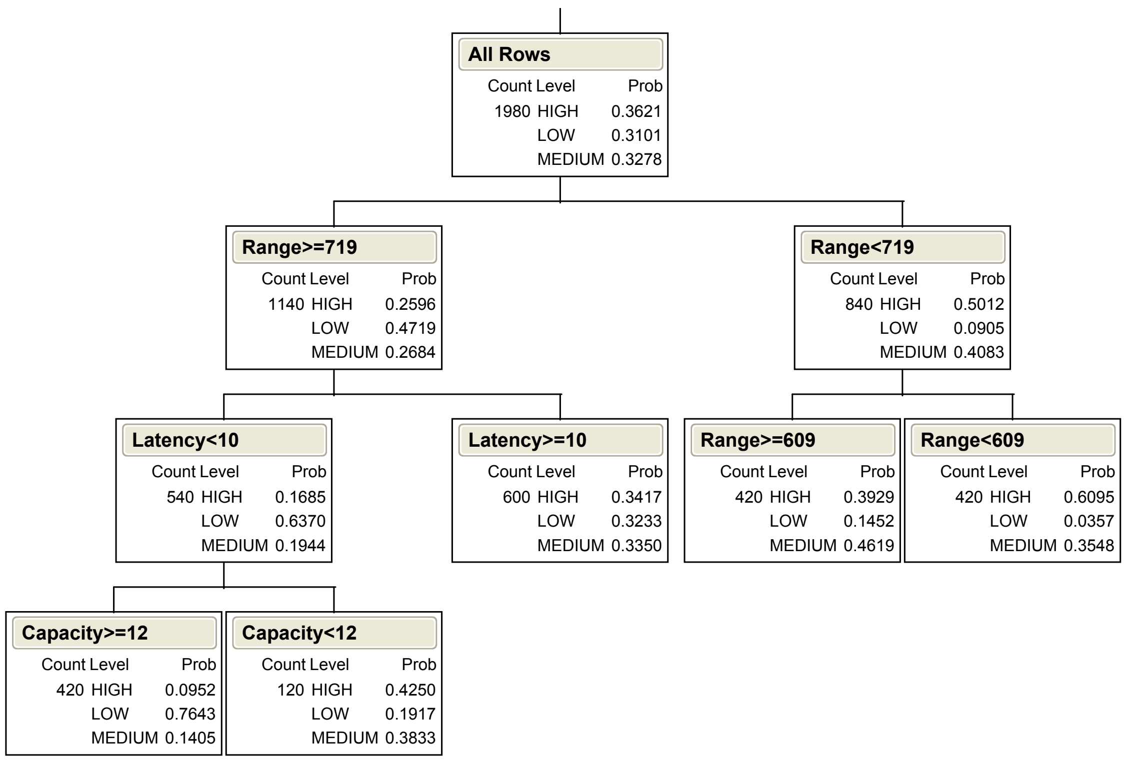

Figure 23. Classification Tree (No EW, 50% Enemy Breakpoint / Blue Casualty MOE)

It is noted that casualties are generally classified as low or medium with higher probability when range is at least 719 and latency is at less than 10 (meaning that communications are received by the sender within one minute of sending). Further, when capacity is less than 12, casualties are generally classified as high with greater probability. It is noteworthy that both tree analyses presented yield comparative results with the multiple regression model presented earlier. This type of analysis can be extended to include the time of battle MOE. These regression and classification trees indicate similar results and are included in Appendix B.

The reader may notice that the analysis presented in this section has not indicated any significance to the two Blue force tactical considerations of early and late UAV priority of effort. Recall that these factors are used to focus UAV efforts on a particular enemy asset (dismounts, armor, air defense and mortars) at various points in the battle. One of these categorical variables, much like the observations in the pre-production experiment sets, tends to overwhelm the communication factors of interest and was omitted from the analysis presented, but is examined in further detail below.

Analysis shows that while late UAV effort is insignificant in all regression analysis, one particular level of early UAV effort stands out. The regression coefficients of these two variables yield significant insights however for the tactical commander. When the factor of early UAV effort is included in the analysis, three of the settings are significant (dismounts, armor and mortars), accounting for a combined 20 percent of the total explained variance in the model. Table 13 shows the regression coefficients for one representative example (enemy breakpoint of 75 percent using Blue casualties as the response).

Early UAV Priority of Effort	Regression Coefficient Value
Dismounts	-21.87
Armor	4.90
Mortars	3.70

Table 13. Early UAV Effort Coefficients (EW, 75% Enemy Breakpoint / Blue Casualties MOE)

Notice the negative coefficient when the UAVs have a priority to focus on the enemy dismounts. Noting that the response in this example is the number of Blue casualties, the greatest "bang for the buck" occurs when dismounts are the primary focus of early UAV effort. Focusing on the armor and mortar assets actually increases the expected number of Blue casualties, while focusing UAV efforts on the enemy dismounts shortens the expected length of the battle and Blue losses.

A tactical commander might be tempted to focus their UAV reconnaissance assets on high value targets such as armor and mortar assets. However, in this scenario at least, it would appear that these UAV assets are better utilized by identifying and providing targeting information on the dismounted defensive positions. Noteworthy is the fact that the primary Blue killing system during the early battle is the NLOS systems. By design (and tactical insight as well) NLOS systems are much more effective against dismounted forces than armor.

2. Network Attack Significance Analysis

The previous section uncovered several communication factors and levels where they are important to the FCS. The second portion of this analysis focuses on how the FCS is affected when the enemy possesses and chooses to use an EW capability. The goal is to uncover insights for the third analysis question.

- How do network attacks (complete and partial degradation) and the Future Force's ability to respond to the attacks hamper fighting ability?

We examine this question using the second experimental data set. Recall that this experimental set varies seven communication factors, two tactical employment factors (UAV employment focus) and the time and duration at which the enemy employs EW. This is done at the two representative enemy breakpoints. The Blue forces are assumed to have "good" communications prior to the attack, and during the attack, the communication factors are degraded.

This analysis is conducted identically as the previous section, namely, by identifying significant factors using multiple regression and then determining levels at which those factors are significant using regression and classification trees. As with the previous analysis, the data is analyzed using both MOEs. A consolidated table is shown in Table 14 which contains the "top" five significant factors for the data sets and MOEs.

Enemy Breakpoint/MOE	Rank	Factor	Sum of Squares
50 percent / Blue Casualties ($R^2 = 0.69$)	1	Range	178.93
	2	Latency	119.42
	3	Capacity	114.83
	4	Time of EW	68.03
	5	Duration of EW	39.42
50 percent / Time of Battle ($R^2 = 0.62$)	1	Range	3725.32
	2	Latency	2697.46
	3	Time of EW	2289.50
	4	Capacity	1977.16
	5	Duration of EW	1048.27
75 percent / Blue Casualties ($R^2 = 0.59$)	1	Range	269.24
	2	Latency	229.87
	3	Range / Time of EW Interaction	153.23
	4	Time of EW	101.09
	5	Capacity	56.91
75 percent Time of Battle ($R^2 = 0.58$)	1	Latency	7664.42
	2	Range	6146.54
	3	Early UAV Effort	5598.21
	4	Time of EW	4020.55
	5	Duration of EW	2980.23

Table 14. Factor Significance for Experimental Design Set Two

Aggregating these results into a single table which shows the prominence of factors examined in these data sets helps to detect recurring patterns in the analyses. Table 15 records the number of times a specific factor appeared in the four regression analyses.

Factor	Number of Times Deemed Significant
Range	4
Latency	4
Time of EW	4
Capacity	3
Duration of EW	3
Early UAV Effort	1
Range / Time of EW Interaction	1

Table 15. Aggregation of Significant Factors (EW / All MOEs & Enemy Breakpoints)

The overlap of significant factors gives insight concerning the importance of factors. The fact that range, latency and time of EW occur in all data sets using both MOEs is again noteworthy. This suggests that these factors could be the prominent communication factors which have an effect on the effectiveness of the FCS in this setting. As well, capacity and the duration of EW (Blue force response to the attack) appear to be prominent.

With these insights on the prominent communications factors, further analysis is conducted to determine the levels where these factors are significant. To examine this question, regression and classification trees are constructed. Guided by the regression analysis, a few key points can be taken away from the regression tree shown in Figure 24.

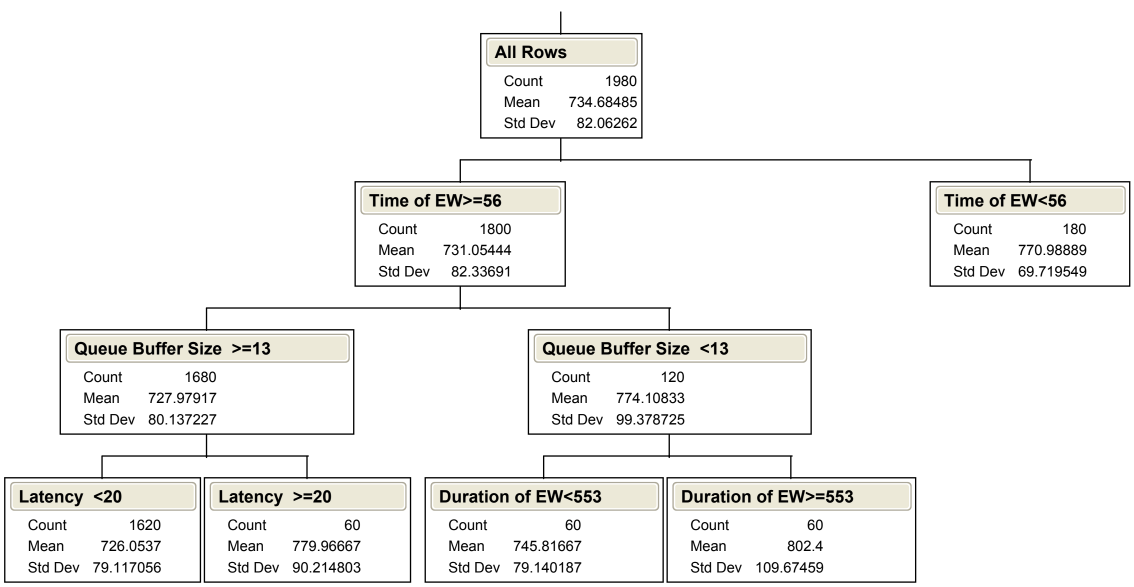

Figure 24. Regression Tree (EW, 75% Enemy Breakpoint / Time of Battle MOE)

The first point that may be extracted from this tree is that when the enemy chooses to employ their EW assets early in the battle, the battle length is generally longer. Note the right side of the tree where the enemy EW is employed very early yields a comparatively high time of battle. Secondly, when the communication system has a limited message queuing ability, battle lengths also tend to be longer. The final observation is that if queue buffer size is large enough for the FCS, the Blue forces must also have a responsive network to provide a "quick" decisive battle.

A comparative analysis using a classification tree where the times of battle are segregated into three quantiles (lower, middle and upper—representing low, medium and long duration battles) shows similar results.

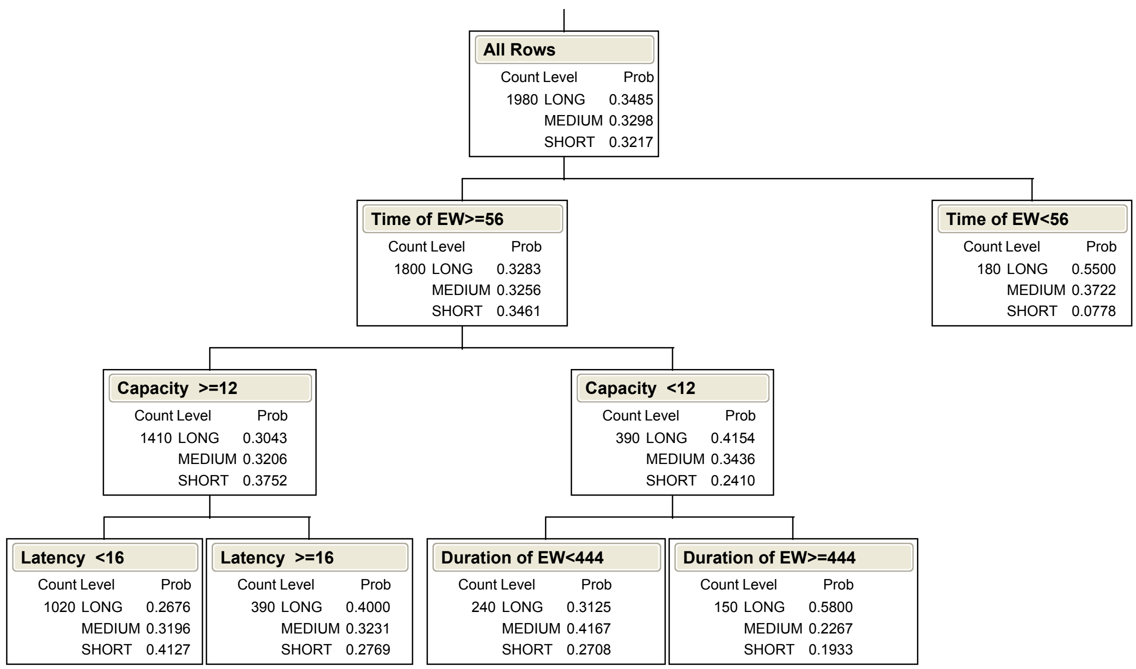

Figure 25. Classification Tree (EW, 75% Enemy Breakpoint / Time of Battle MOE)

It is noted that the time of battle is generally classified as long when the enemy chooses to employ their EW early in the battle. Additionally, increased capacity and decreased latency are important capabilities when a short duration battle is desired. Once again, these observations are representative of the analysis conducted with regression and classification trees and these trees are presented in Appendix B.

3. Most Vital Link Analysis

As discussed earlier, this analysis shifts focus from the FCS operating in a degraded communications environment to conducting operations in an environment where complete degredation is experienced in a particular battlefield operating system. This corresponds to the fourth and final research question.

- If destroyed or hampered, which communication link(s) most affect the Future Force in terms of mission accomplishment?

Once again, using the analysis template shown in the previous two sections, we examine this question using the third experimental data set. Recall that this experimental set varies the activation times of each enemy EW system over many levels. This is once again done at the two representative enemy breakpoints. The Blue forces are assumed to have "good" communications prior to the attack, and during the attack, the communication link is severely degraded. A consolidated table of regression results is shown in Table 14 which contains the rank ordered importance of the communication links for the data sets and MOEs.

Enemy Breakpoint/MOE	Rank	Factor	Sum of Squares
50 percent / Blue Casualties ($R^2 = 0.85$)	1	Armor Communication Link	1725.89
	2	UAV Communication Link	47.39
	3	Dismount Communication Link	23.87
50 percent / Time of Battle ($R^2 = 0.89$)	1	Armor Communication Link	38268.92
	2	UAV Communication Link	938.05
	3	Dismount Communication Link	713.04
75 percent / Blue Casualties ($R^2 = 0.90$)	1	Armor Communication Link	3960.14
	2	UAV Communication Link	224.60
	3	Dismount Communication Link	12.18
75 percent Time of Battle ($R^2 = 0.85$)	1	Armor Communication Link	303643.61
	2	UAV Communication Link	4197.16
	3	Dismount Communication Link	1392.69

Table 16. Factor Significance for Experimental Design Set Three

It is shown that a linear model which contains only main effects yields a fairly well-fit model. Any interaction terms, while informational, yields little additional insight to the problem at hand. Noteworthy is the great disparity of the significance between the armor communication link and the dismount and UAV communication links. The armor communication link is clearly the most significant factor when a particular battlefield operating system is targeted by enemy EW.

While regression and classification trees have been shown to reveal insights about the data in the previous two systems, when such a great disparity exists in factor importance, these tools offer little insight to the problem. In essence, these trees reveal that the earlier in the battle that the enemy cuts the armor communication link, the worse off it is for the Blue forces. With that, a possible explanation for this behavior is warranted.

One reason for the significance of the armor communication link is that the armor assets have substantial sensing abilities. Many redundant and complimentary means of identifying enemy targets (radar, enhanced optical, thermal sensors) mounted on a mobile platform makes the armor assets both a key killing and *sensing* asset. The armor assets, when unable to relay their enemy intelligence essentially takes a very significant NLOS system targeting ability away from the FCS. This significantly diminishes the effects of a combined arms battle. In essence, the FCS, instead of being a system of complimentary systems, becomes a unit that fights a series of independent battles within battlefield operating systems (infantry fighting infantry, tanks fighting tanks, NLOS systems providing fires only on their organic sensing assets).

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VI. CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE STUDIES

A. SUMMARY

Each of the designed experimental sets and corresponding analysis provides findings to consider when designing a communication system to support the FCS. As the US Army proceeds into the system design and development stage of acquisition of these systems, some useful insights from this analysis should be taken into account.

Firstly, this analysis, while believed by the author to be beneficial, must not be overstated. All conclusions are derived from analysis based on output from a low to medium resolution model that should be viewed as a distillation tool. While believed to be free of major bugs and modeling errors, the analysis does not take into account physical aspects of modeling communication effects. Since the beginning of this analysis, tools have been developed to examine these effects in a high resolution model setting. Insights gleaned from this analysis should be examined in greater detail using these models. Additionally, conclusions drawn are for only one mission set (attack) of many mission sets that the FCS must be capable of operating in.

With that disclaimer, it should be noted that a viable communication network *IS* important to the FCS. This network requires special attention when designing its characteristics and should be treated as a *MAIN* component of the FCS. If a communication network is unable to support the integration of all of the battlefield operating systems, the increased mobility, sensing and targeting abilities of the FCS are for naught. The levels of importance shown in Chapter V, should be used as a starting point for future analysis to focus precious modeling time on high-resolution models. A summary of those findings are shown below.

- While believed that communication range will not be an issue with evolving communications equipment, the Army must be sure of this. Even a degradation of 25 percent on the ability to communicate over the entire battlespace could have dramatic consequences for the FCS. While tactically the Army " adapts and overcomes" issues during combat and would be able to mitigate some of the consequences of diminished communication range, this process takes time and affects all units involved.

- An unresponsive or slow network is nearly as detrimental to the FCS as diminished communications range. It has been shown in this analysis that when intelligence on a fairly static enemy employed in the defense is delayed, the battle time is extended and Blue forces generally pay for that delay in casualties. Future high-resolution modeling should look at network delays greater than one minute to gain the most from these simulations. Additionally, it has been shown that the network capacity can easily be overwhelmed and system designers should look at the required bandwidth to ensure a capable FCS. Finally, while not modeled in this analysis, the responsive network also has fire control system design implications as well. Any fire control system must be designed with timely response in mind. A round from an NLOS system delivered too late is wasted effort.

- Reliability, while important, is not as significant in a system with many means of redundancy (such as the FCS). Even if a substantial amount of communication links are unable to relay enemy intelligence, there are many others that are able to "pick up the slack."

- Enemy electronic warfare assets must not be underestimated and should be a focus of any pre-engagement intelligence activities. As indicated, even a limited attack on a particular battlefield operating system (armor assets), could prove to be costly for the FCS.

- Tactical insights such as those presented in pre-production observations must be noted. NLOS systems, when performing as specified, present an incredible asset which can set the tone for FCS battlefield success and must be allowed to attrite the enemy as long as possible. Additionally, the effects of combat multipliers such as phychological operations should be an integral part of the FCS operational and organizational structure to help set the tone for a successful battle. Finally, intuition should be confirmed to ensure proper prioritization of limited UAV assets. A correct prioritization of effort could assist the FCS in any tactical goal.

B. RECOMMENDATIONS FOR FUTURE RESEARCH

It has been said that any good analysis uncovers many more questions than originally posed. While no assertions are made as to the quality of this analysis, there are significant questions still left to be examined in the communications realm of the FCS implementation. The analysis presented is a single "data point." This analysis has drawn conclusions based on an enemy employed in the defense. The Blue forces are assumed to have had sufficient preparation time to survey the enemy and forge battle plans.

One of the major "selling points" of the FCS is that it is a "strategically responsive, precision maneuver force, dominant across the range of military operations."[41] This alone warrants more investigation on the communications effects in other settings such as MOUT, low intensity conflict, defensive, and movement to contact operations. This analysis could be used as a launch point, using MANA as the platform. All agents have been designed, taking great care to model stated performance parameters and could be used for further analysis.

Further research could examine how other agent-based models could augment or even contradict findings presented in this thesis. For other, more detailed analytic effort, this scenario could be used to guide analysis in a high-resolution combat model such as CASTFOREM to uncover physics-based insights on communications behavior.

Finally, factors such as weapons effectiveness were not explicitly explored to uncover other insights that may be significant to the FCS. Should the combined effects of a degraded communications network and decreased specified weapons effectiveness be of interest, this analysis could serve as a launch point for future analysis.

The MANA scenario files and Excel modeling files discussed are both available by contacting CPT Joseph Lindquist, United States Military Academy, Department of Mathematical Sciences, West Point, New York, or by email at joseph.lindquist@us.army.mil .

41 US Army Training and Doctrine Command, *The Army Future Force: Decisive 21st Century Landpower, Strategically Responsive, Full Spectrum Dominant,* p. 2.

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APPENDIX A. WEAPON CHARACTERISTICS

Raw Blue force characteristics:

			NLOS-Mortar	ICV	MCS	C2V	ARV-A	ARV-RSTA	UAV - CL I	UAV - CL II
Lethality										
	Pri - weapons		120mm B/LOS		120 mm		M-230 / 30mm	M-230 / 30mm		
	Unguided	**Fire Rate (L) - RPM**	8		4		625	625		
		Fire Rage (H) - RPM	10		4		625	625		
		Range (L) - meters			2000		6000	6000		
		Range (H) - meters	1000		4000		6000	6000		
		Basic Load - rounds	65		43		1200	1200		
	Guided	**Fire Rate (L) - RPM**	8		4					
		Fire Rage (H) - RPM	10		4					
		Range (L) - meters	12000		2000					
		Range (H) - meters	15000		16000					
		Basic Load- rounds	65		43					
		Lethal Radius - meters	60							
	Type CSW									
		M2 / MK 44*	1	1	1					
		Mk-19 / XM 307 *	1		1	1				
		M240B								
		CE APS		1	1	1				
		Mk-44		1						
		Stinger/Dis		1						
		Javelin/Dis		X			4			
Survivability										
	Ballistic protection		AT-M	AT-M	AT-M	AT-M	AT-M	AT-S		
	Employ Obscurants		X	X	X	X	X	X		
	Mine Detection		X	X	X	X	X	X		
	Obs/Mine Destruction				X					
	Obs/Mine marking		X	X	X	X	X	X		
Mobility										
	Speed									
		Hard surf	90	90	90	90	90	90	60	100
		x-cntry - kph	50	50	50	50	50	50	60	100
		dash	0-48/ 8s	0-48/ 8s	0-48/ 8s	0-48/ 8 s	0-48/12s	0-48/12s		
Sensing	**Type**		Radar Plus	Radar Basic	Radar Basic	Radar Plus	Radar Basic	Radar Plus	UAV Basic	UAV Basic
	autonomous - meters									
	semi-autonomous - meters		500	500	500	500				
UAV Char.	**Time on Station (Min)**								90	300
	Sensor Capability								Low	Low
Robotics	**UAV LaunchControl**			CL-I	CL-I	CL-I				
	SUGV			X	X					
Comms Capability			M	H	M	H	L			

Ballistic Protection - Armor Prtotection (small, medium, large)
CSW - close support weapons - * indicates one or the other
UAV Sensor Capability (Low, Medium, High)
Comms Capability - Low, Medium, High
XM 307 substitute MK-19 / M2

Blue force Characteristics Continued:

					CSW Weapon Specs							
UGV (Small)	UAV - CL III	R&SV	NLOS Cannon	NLOS LS	M2	MK44	M240B	MK19	XM 307	Infantryman	Javelin	Stinger
			155mm	PAM						M16		
					40	40	100	40	40	12	0.5	0.5
					40	200	100	40	40	15	0.5	0.5
					100	100	100	100	100	100	65	2000
					1830	1500	1800	1600	2000	550	2500	4500
					2000	1000	1000	430	430	240	1	1
			2	2								
			2	2								
			3000	40000								
			40000	60000								
			48	15								
			80									
			1									
		1	1									
AT-S		AT-M	AT-M	AT-S								
		X	X									
		X	X									
		X	X									
	200	90	90							6		
	200	50	50									
		0-48/ 8s	0-48/ 8s									
Electro Optical Basic	UAV Extended	Radar Plus	Radar Plus	Electro Optical Basic						Electro Optical Basic	Electro Optical Extended	Radar Basic
			500									
	360											
	Med											
L			M	L								

Blue force MANA converted characteristics:

Four Digit Grid									
X1	X2	Difference in Meters		MANA Battlefield Size		Conversion Factor (Meters / Pixel)			
4925	6405	14800		1000	Square	14.8			
Real Time	Mana Steps	Conversion Factor (Hr / Time Step)							
1 min	15	0.00111							
		NLOS-Mortar	**ICV**	**MCS**	**C2V**	**ARV-A**	**ARV-RSTA**	**UAV - CL I**	**UAV - CL II**
Pri - weapons		120mm B/LOS		120 mm		M-230 / 30mm	M-230 / 30mm		
Unguided	**Fire Rate (L) - RPS**	0.053		0.027		4.167	4.167		
	Fire Rage (H) - RPS	0.067		0.027		4.167	4.167		
	Range (L) - pixels			135.1		405.4	405.4		
	Range (H) - pixels	67.6		270.3		405.4	405.4		
	Basic Load - rounds	65.0		43.0		1200.0	1200.0		
Guided	**Fire Rate (L) - RPS**	0.053		0.027					
	Fire Rage (H) - RPS	0.067		0.027					
	Range (L) - pixels	810.8		135.1					
	Range (H) - pixels	1013.5		1081.1					
	Basic Load- rounds	65.0		43.0					
	Lethal Radius - pixels	4.1							
Type CSW									
	M2 / MK 44*	1	1	1					
	Mk-19 / XM 307 *	1		1	1				
	M240B								
	CE APS		1	1	1				
	Mk-44		1						
	Stinger/Dis		1						
	Javelin/Dis		X			4			
Ballistic protection		AT-M	AT-M	AT-M	AT-M	AT-M	AT-S		
Employ Obscurants		X	X	X	X	X	X		
Mine Detection		X	X	X	X	X	X		
Obs/Mine Destruction				X					
Obs/Mine marking		X	X	X	X	X	X		
Speed									
	Hard surf	6.76	6.76	6.76	6.76	6.76	6.76	4.50	7.51
	x-cntry - pix/ts	3.75	3.75	3.75	3.75	3.75	3.75	4.50	7.51
	dash	0-48/ 8s	0-48/ 8s	0-48/ 8s	0-48/ 8 s	0-48/12s	0-48/12s		
Type		**Radar Plus**	**Radar Basic**	**Radar Basic**	**Radar Plus**	**Radar Basic**	**Radar Plus**	**UAV Basic**	**UAV Basic**
Time on Station (Min)								90	300
Sensor Capability								Low	Low
autonomous (pixels)									
semi-autonomous (pixels)		33.8	33.8	33.8	33.8				

Blue force MANA converted characteristics continued:

UGV (Small)	UAV - CL III	R&SV	NLOS Cannon	NLOS LS	M2	MK44	M240B	MK19	XM 307	Infantryman	Javelin	Stinger
			155mm	PAM						M16		
					0.267	0.267	0.667	0.267	0.267	0.080	0.033	0.033
					0.267	1.333	0.667	0.267	0.267	0.100	0.033	0.033
					6.8	6.8	6.8	6.8	6.8	6.8	4.4	135.1
					123.6	101.4	121.6	108.1	135.1	37.2	168.9	304.1
					2000.0	1000.0	1000.0	430.0	430.0	240.0	1.0	1.0
			0.013	0.013								
			0.013	0.013								
			202.7	2702.7								
			2702.7	4054.1								
			48.0	15.0								
			5.4									
			1									
		1	1									
AT-S		AT-M	AT-M	AT-S								
		X	X									
		X	X									
		X	X									
	15.02	6.76	6.76							0.450		
	15.02	3.75	3.75									
		0-48/ 8s	0-48/ 8s									
Electro Optical E	UAV Extended	Radar Plus	Radar Plus	Electro Optical I						Electro Optical Basi	Electro Optical Exte	Radar Basic
	360											
	Med											
			33.8									

Red Force characteristics:

			BMP-3	82mm Mortar	SA-16 Infantryman	RPG-7	AT-7	RPK-74	AK-M Infantryman	SVD
Lethality										
	Pri - weapons		2A-42 / 30mm							
	Unguided	Fire Rate (L) - RPM	200	8		1	0.5	50	12	1
		Fire Rage (H) - RPM	300	10		1	0.5	50	15	1
		Range (L) - meters	1500	1000		50	40	460	400	800
		Range (H) - meters	4000	4000		100	1500	460	400	1000
		Basic Load - rounds	1000	65		3	2	1000	240	10
	Guided	Fire Rate (L) - RPM			0.5					
		Fire Rage (H) - RPM			0.5					
		Range (L) - meters			5000					
		Range (H) - meters			5000					
		Basic Load- rounds			1					
		Lethal Radius - meters		60						
	Type CSW									
		SA-16 ATGM	1		1					
Survivability										
	Ballistic protection		AT-M							
Mobility										
	Speed									
		Hard surf	70	6	6	6	6	6	6	6
		x-cntry - kph	40	6	6	6	6	6	6	6
Sensing	Type		Electro Optical Extended	Electro Optical Basic	Radar Extended	Electro Optical Basic	Electro Optical Extended	Electro Optical Basic	Electro Optical Basic	Electro Optical Extended
Comms Capability	Commo Capability		M	M	M	L	L	L	L	M

Red Force MANA converted characteristics:

		BMP-3	82mm Mortar	SA-16 Infantryman	RPG-7	AT-7	RPK-74	AK-M Infantryman	SVD
Pri - weapons		2A-42 / 30mm							
Unguided	Fire Rate (L) - RPS	1.33	0.53		0.01	0.03	0.33	0.08	0.07
	Fire Rage (H) - RPS	2.00	0.67		0.07	0.03	0.33	0.10	0.07
	Range (L) - pixels	101.35	67.57		3.38	2.70	31.08	27.03	54.05
	Range (H) - pixels	270.27	270.27		6.76	101.35	31.08	27.03	67.57
	Basic Load - rounds	1000.00	65.00		3.00	2.00	1000.00	240.00	10.00
Guided	Fire Rate (L) - RPS			0.03					
	Fire Rage (H) - RPS			0.03					
	Range (L) - pixels			337.84					
	Range (H) - pixels			337.84					
	Basic Load- rounds			1.00					
	Lethal Radius - pixels		4.05						
Type CSW									
	SA-16 ATGM	1		1					
Ballistic protection		AT-M							
Speed									
	Hard surf	5.26	0.45	0.45	0.45	0.45	0.45	0.45	0.45
	x-cntry - kph	3.00	0.45	0.45	0.45	0.45	0.45	0.45	0.45
Type		Electro Optical Extended	Electro Optical Basic	Radar Extended	Electro Optical Basic	Electro Optical Extended	Electro Optical Basic	Electro Optical Basic	Electro Optical Extended
Commo Capability		M	M	M	L	L	L	L	M

Sensing characteristics:

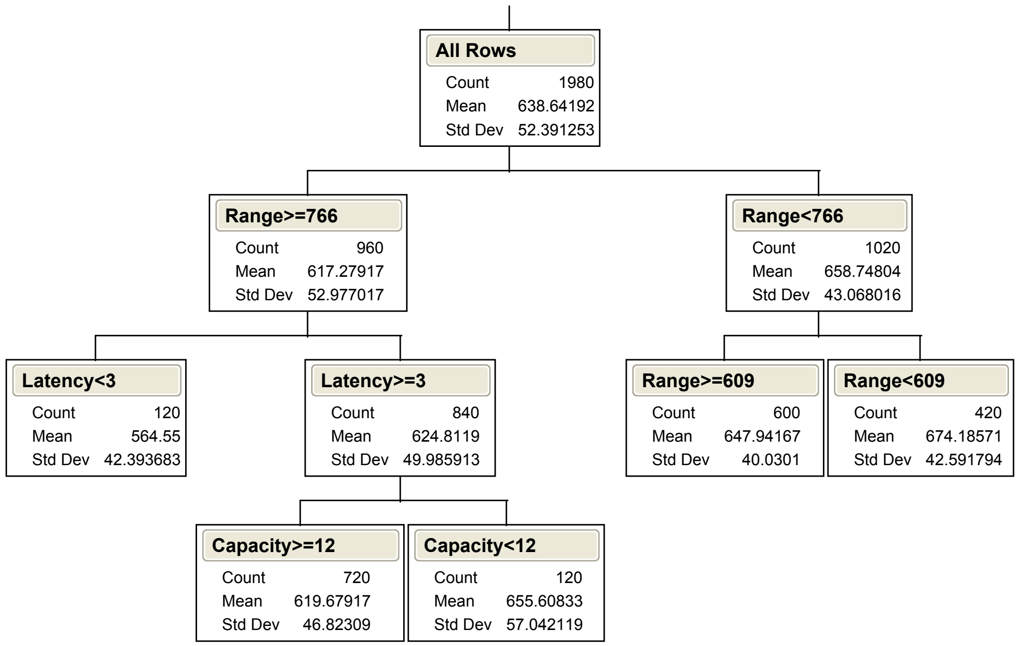
Sensor Types												
Electro Optical Basic												
Electro Optical Extended												
Radar Basic												
Radar Extended												
Radar Plus												
UAV Basic												
UAV Extended												
	Range (meters)	100	200	400	600	800	1000	2000	3000	4000	5000	6000
	Range (Pixels)	6.8	13.5	27.0	40.5	54.1	67.6	135.1	202.7	270.3	337.8	405.4
EO (Lock)												
basic	Range PC	0.95	0.80	0.50								
extended	Range PC	0.95	0.80	0.70	0.60							
Radar (Max+10%)												
basic	Range PC	0.95	0.90	0.80	0.70	0.6	0.5					
extended	Range PC						0.90	0.40		0.30	0.20	0.1
Plus	Range PC			0.99			0.8		0.7			
	Range (meters)	45	59	74		200						
UAV (Max +10%)	**Range (Pixels)**	3.0	4.0	5.0	0.0	13.5	0.0	0.0	0.0	0.0	0.0	0.0
basic	Range PC	0.9	0.8	0.7								
extended	Range PC	0.9	0.8	0.7		0.6						

Force overview:

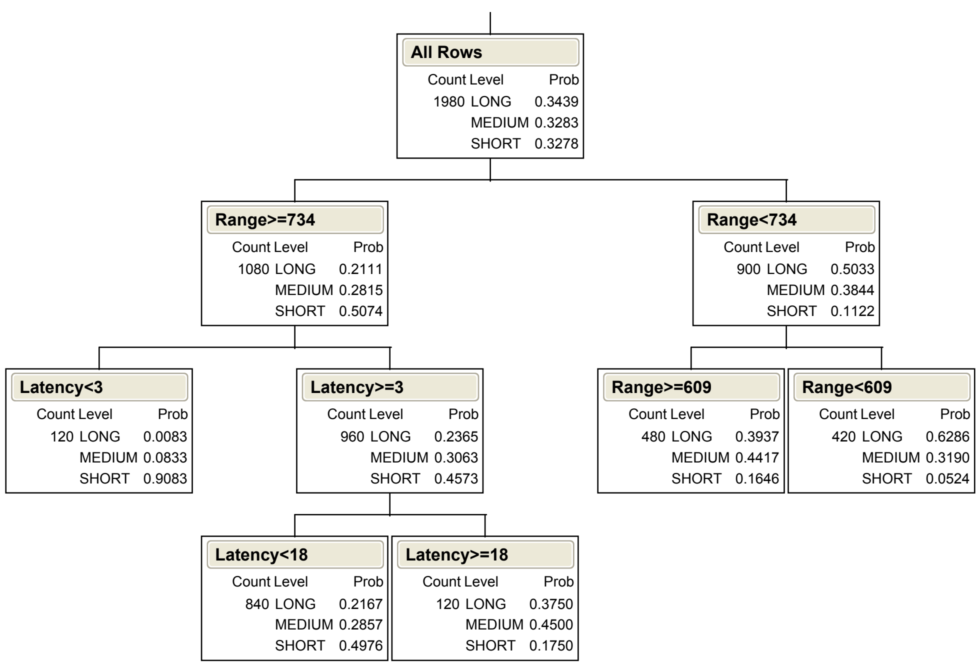
	Squad number	Agents	Class	Primary Target	Non-Target	Inorganic Comms	Wpn #	Rds	Pen
Riflemen	1	63	100		200,3	4,5	1	240	0
ATGM	2	6	100	3	200	4,5	1	1	5
Automatic Rifleman	3	9	100		200,3	4,5	1	600	0
Dismounts Good	4	1	200	100		1,2,3			
Dismounts Deg	5	1	200	100		1,2,3			
RSV PLT	6	3	110		200	8,9	1	1000	0
ARV-RSTA RSV	7	1	110		200	8,9	1	1200	0
RSV Good	8	1	200	110		6,7			
RSV Deg	9	1	200	110		6,7			
MCS	10	3	108	3	200	12,13	1	43	5
							2	1000	0
ARV-RSTA MCS	11	1	108		200	12,13	1	1200	0
MCS Good	12	1	200	108		10,11			
MCS Deg	13	1	200	108		10,11			
ICV	14	12	105		200	16,17	1	1000	0
ARV-A	15	3	105		200	16,17	1	1200	0
							2	4	5
ICV Good	16	1	200	105		14,15			
ICV Deg	17	1	200	105		14,15			
NLOS Mortar	18	4	104		200		1	65	0
							2	2000	0
NLOS Cannon	19	2	111		200		1	48	0
NLOS-LS	20	3	112	3	200		1	15	5
UAV CL I INF PLT	21	3	107			4,5			2
UAV CLI RSV	22	3	107			8,9			2
UAV CL III NLOS	23	2	109			24,25			2
UAV NLOS Good	24	1	200	109		18,19,20			
UAV NLOS Deg	25	1	200	109		18,19,20			
Red Riflemen	26	58	1	100	105,108,109,110	33,32	1	240	0
Red AR	27	9	1	100	105,108,109,110		1	600	0
Red Sniper	28	3	1	100	105,107,108,109,110	33,32	1	10	0
Red RPG	29	9	1	100,105,108,110	107,109		1	3	5
Red Air Defense	30	3	2	0,109	100,104,105,108,110,111,112	33,32	1	1	10
				100	105,108,109,110		2	240	0
Red ICV	32	10	3	100	107,109		1	1000	0
				105,108,110	100		2	2	5
Red Mortar	31	4	4	100	107,109		1	65	0
Jammer	33	1	0	200	ALL OTHERS		1	1000	10

APPENDIX B. ADDITIONAL REGRESSION AND CLASSIFICATION TREES

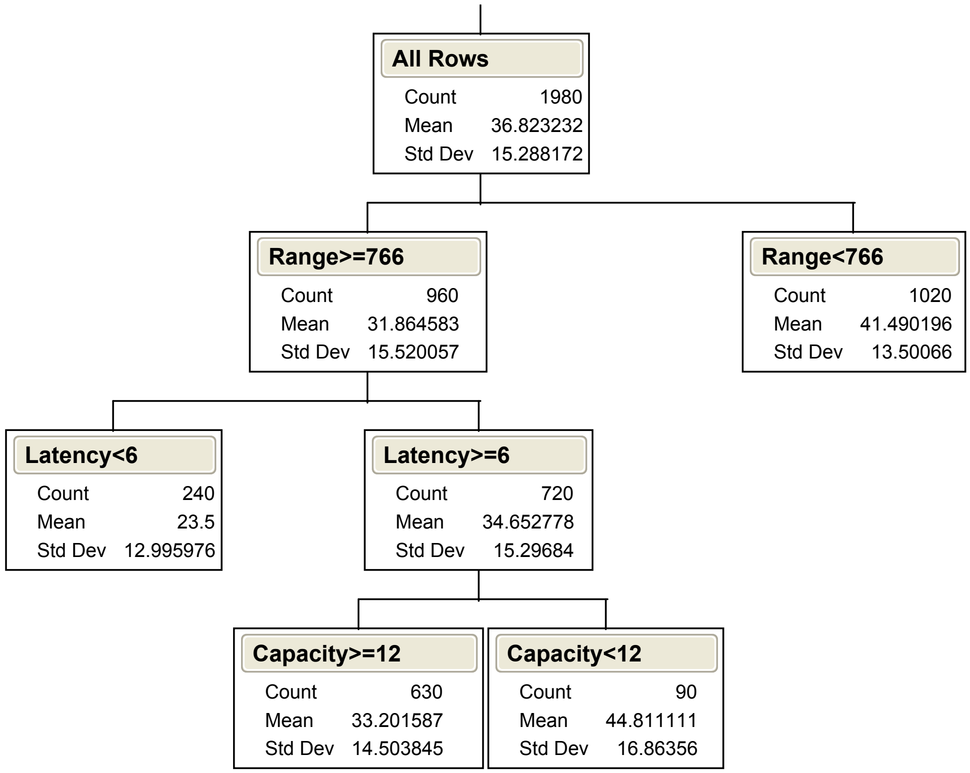
Regression Tree (No EW, 50% Enemy Breakpoint / Time of Battle MOE)



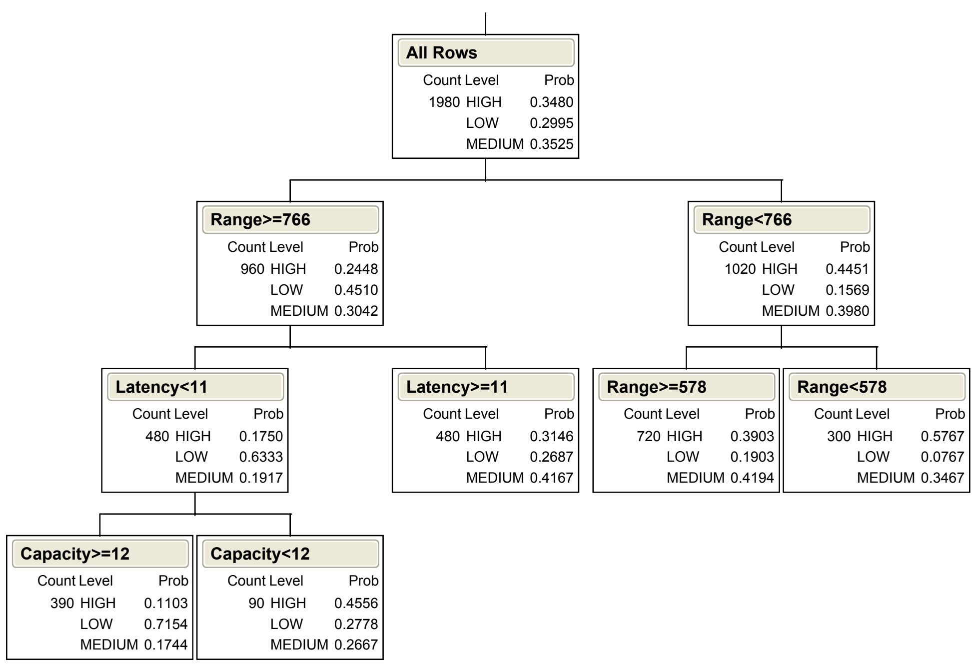
Classification Tree (No EW, 50% Enemy Breakpoint / Time of Battle MOE)



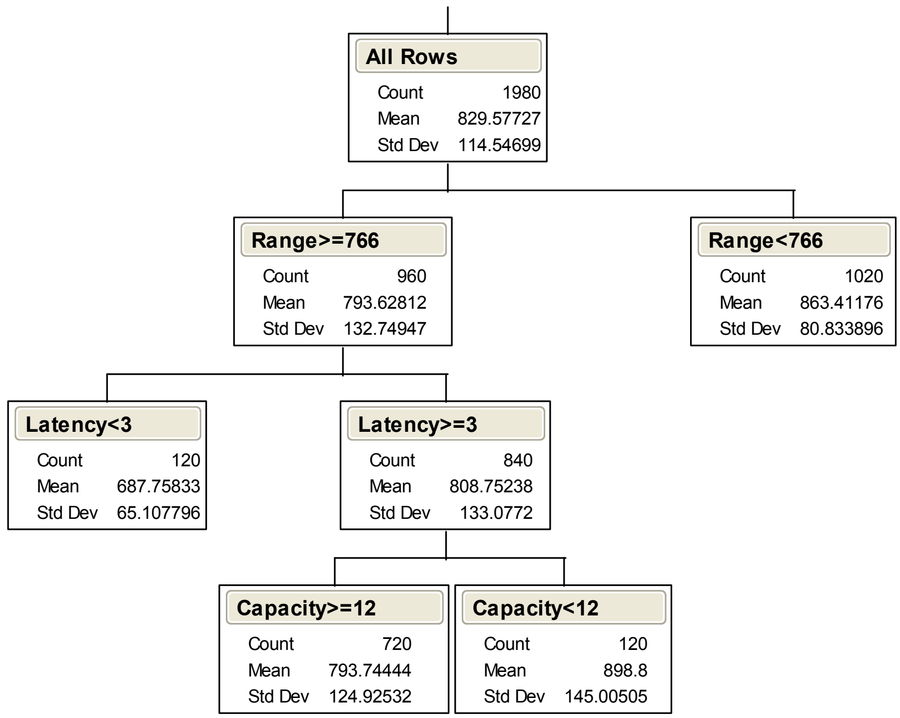
Regression Tree (No EW, 75% Enemy Breakpoint / Blue Casualties MOE)



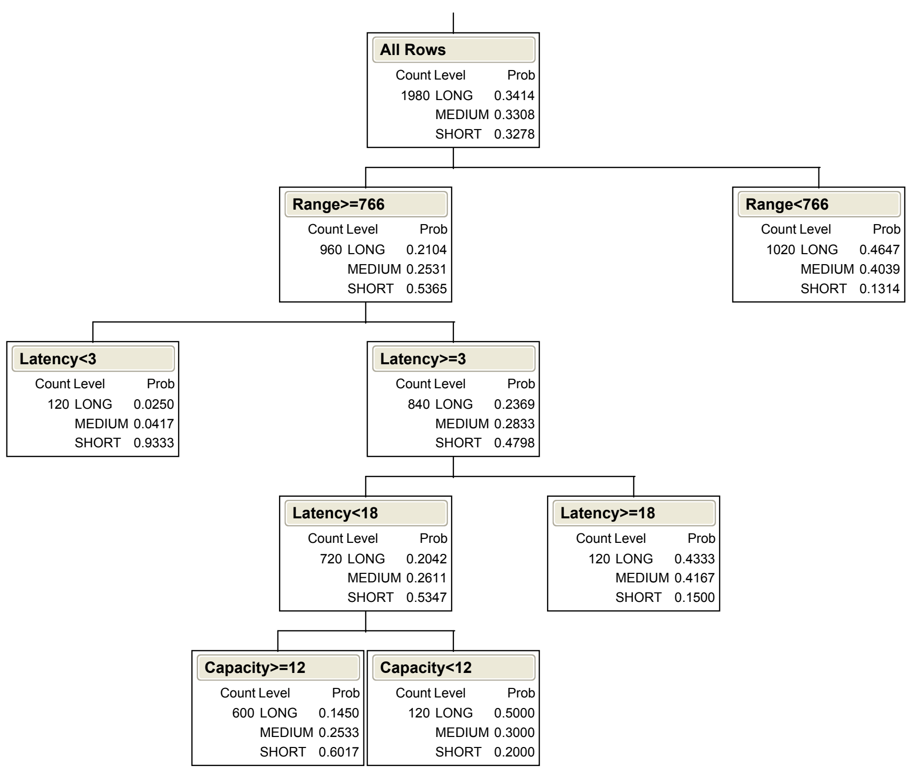
Classification Tree (No EW, 75% Enemy Breakpoint / Blue Casualties MOE)



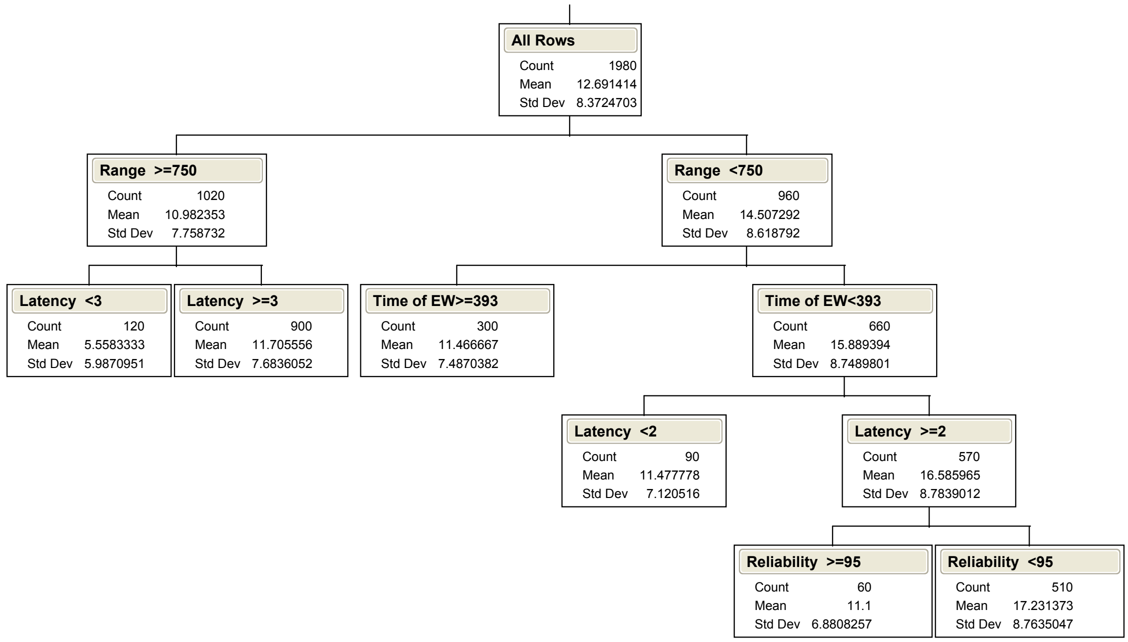
Regression Tree (No EW, 75% Enemy Breakpoint / Time of Battle MOE)



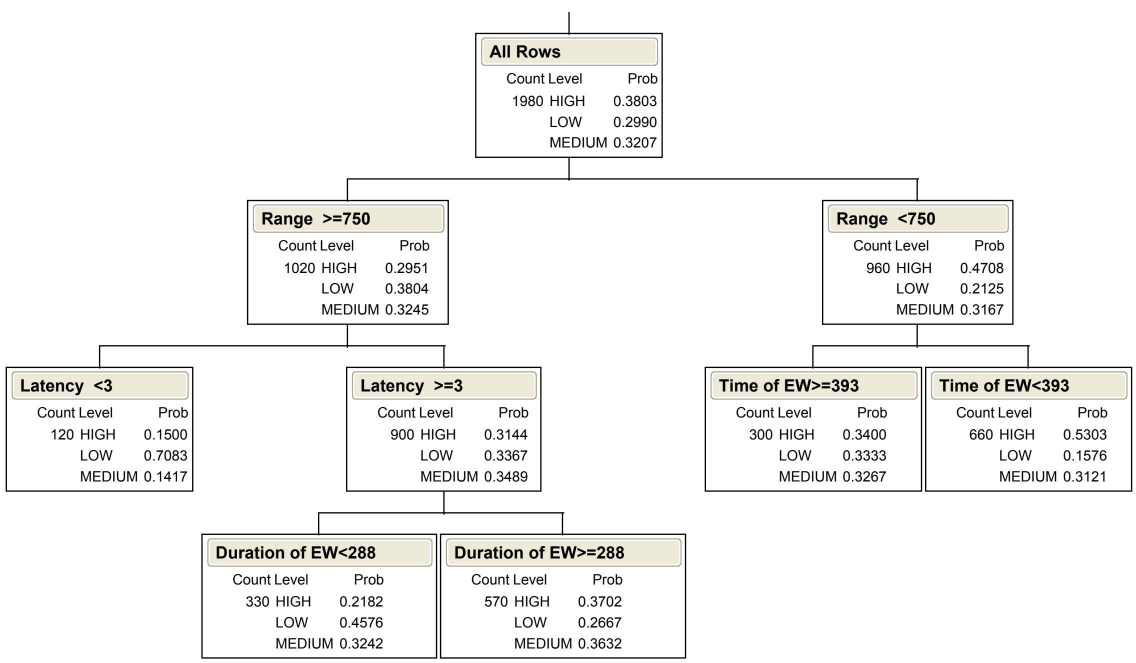
Classification Tree (No EW, 75% Enemy Breakpoint / Time of Battle MOE)



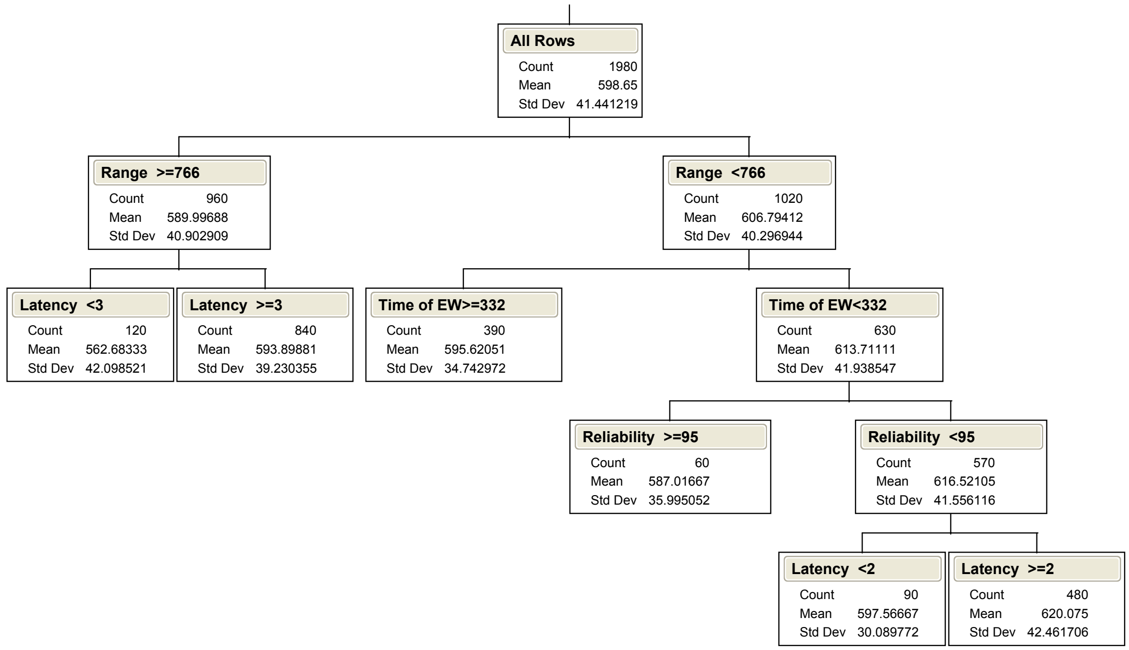
Regression Tree (EW, 50% Enemy Breakpoint / Blue Casualties MOE)



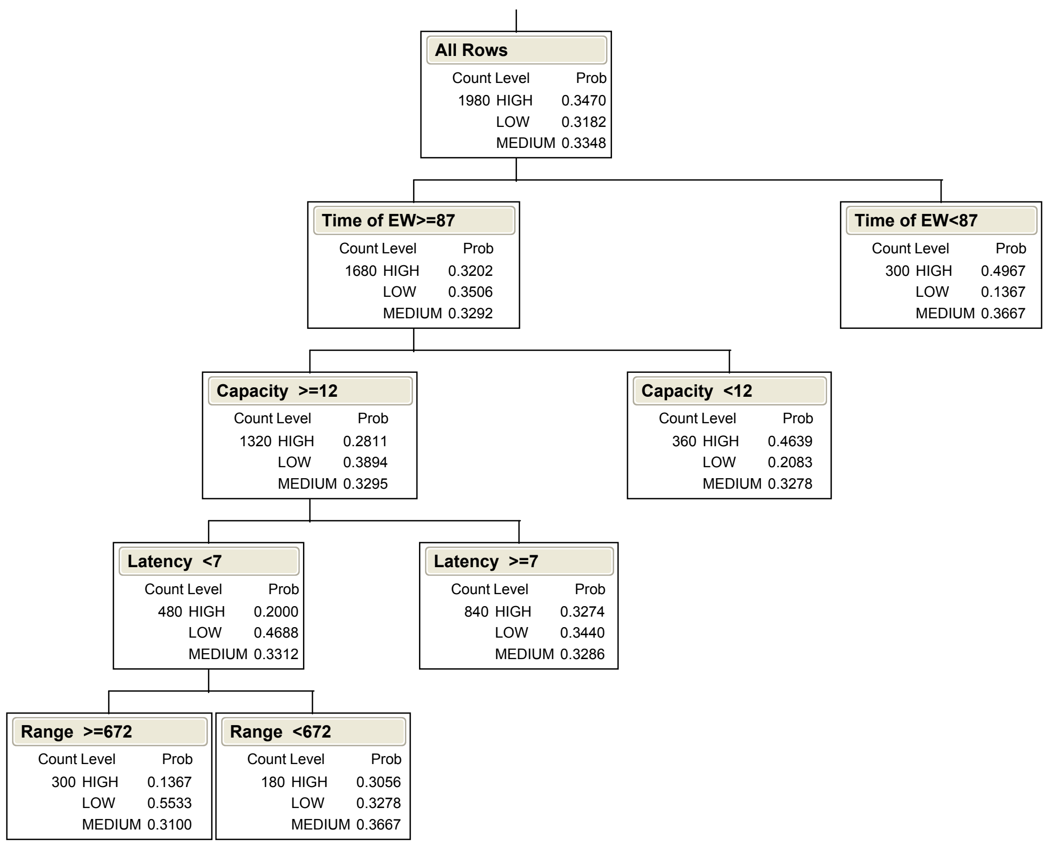
Classification Tree (EW, 50% Enemy Breakpoint / Blue Casualties MOE)



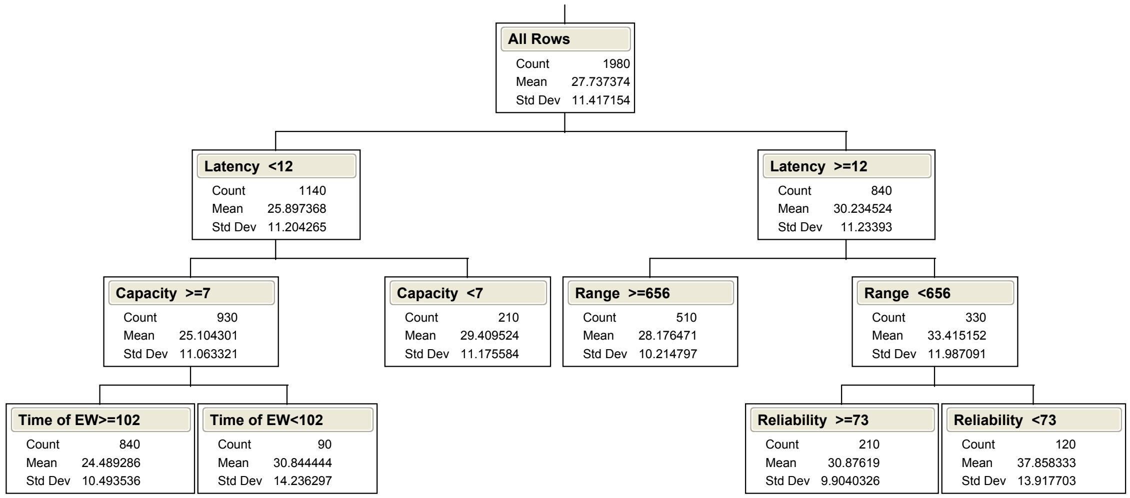
Regression Tree (EW, 50% Enemy Breakpoint / Time of Battle MOE)



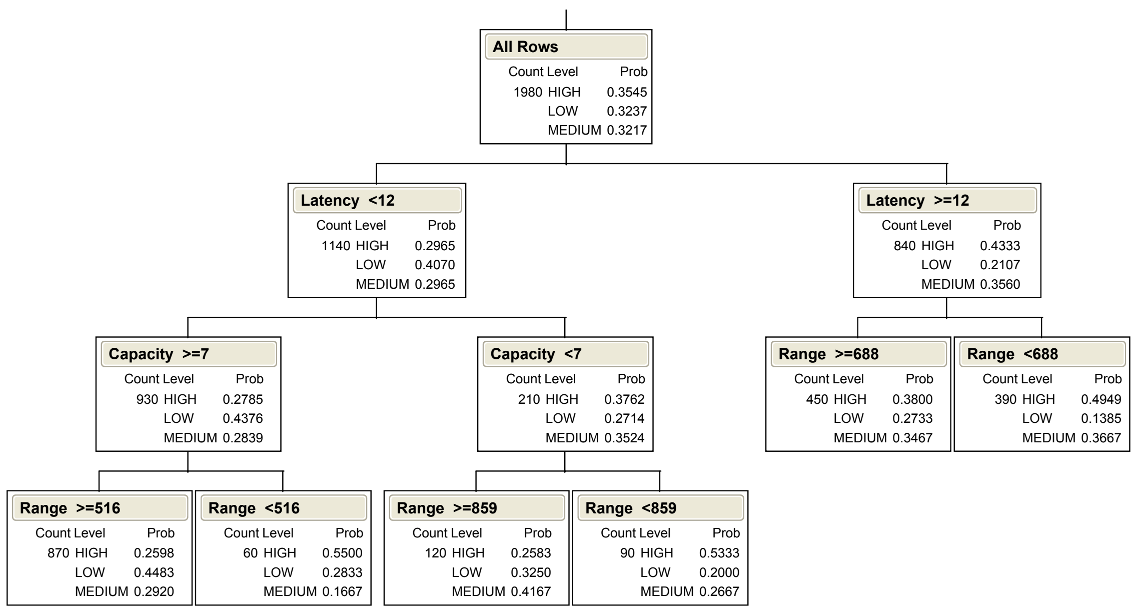
Classification Tree (EW, 50% Enemy Breakpoint / Time of Battle MOE)



Regression Tree (EW, 75% Enemy Breakpoint / Blue Casualties MOE)



Classification Tree (EW, 75% Enemy Breakpoint, Blue Casualties MOE)



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